STRATEGIES TO IMPROVE CROP RECOVERY OF SWINE MANURE NITROGEN

A Thesis Submitted to the College of
Graduate Studies and Research
In Partial Fulfillment of the Requirements
For the Degree of Master of Science
in the Department of Soil Science
University of Saskatchewan
Saskatoon

By
Chadrick A. Carley

PERMISSION TO USE

In presenting this thesis in partial fulfillment for a postgraduate degree from the University of Saskatchewan, I agree that the libraries of this University may make it freely available for inspection. I further agree that permission for copying of this report in any manner, in whole or in part for scholarly purposes be granted by the professor or professors who supervised my work. In the absence of the supervisors, the Head of the Department or the Dean of the College in which my report was done may be approached for such permission. It is understood that any copying or publication of this report or parts thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of Saskatchewan in any scholarly use which may be made of any material in this report.

Requests for permission to copy or to make other use of material in this thesis in whole or in part should be addressed to:

Head of the Department of Soil Science
University of Saskatchewan
51 Campus Drive
Saskatoon, Saskatchewan, Canada
S7N-5A8

ABSTRACT

Intensive swine operations produce large amounts of manure that must be dealt with responsibly. Liquid swine manure (LSM) collected in storage units is applied to cropland as a nutrient source. Maximizing crop utilization of the nitrogen (N) added in manure is important to achieve economic and environmental benefits. The objectives of this research were to evaluate the effect of 1) adding a nitrification inhibitor and 2) using supplemental phosphorus (P) and sulfur (S) fertilizers as means of enhancing crop recovery of LSM-N.

Field experiments were conducted at two long-term manure management sites in Saskatchewan; 1) Dixon (Black Chernozem) and 2) Melfort (Dark Grey Luvisol). At the Dixon site, plant and soil samples were collected throughout the 2005 and 2006 growing season, and ammonium-N (NH_4^+-N) and nitrate-N (NO_3^--N) concentration in soil, and total N content in plant were measured. Plant root simulator (PRS^{TM}) probes were used to measure NH_4^+-N and NO_3^--N supply rates at the Dixon site to determine the effectiveness of a nitrification inhibitor dicyandiamide (DCD) added to LSM. Crop recovery of N applied through LSM application was assessed by measuring seed and straw yield and total N content. The effect of adding supplemental P fertilizer at 6.5 kg P ha^{-1} to swine manure amended soil on N recovery was also evaluated at the Dixon site. At the S deficient Melfort site, the effect of supplemental S fertilizer added at 40 kg S ha^{-1} as ammonium sulfate and elemental S was evaluated.

The addition of DCD (0.275 mL kg^{-1}) to LSM in 2005 and 2006 at Dixon did not significantly affect the proportion of LSM-N recovered or the seed yield. However, measurements of available NH_4^+-N and NO_3^--N concentrations and supply rates at the beginning of the growing season in 2005 indicated that the nitrification inhibitor was effective in keeping more of the LSM-N in the NH_4^+ form for approximately 14 days after LSM application.

The addition of supplemental P fertilizer to plots fertilized with LSM at the Dixon site, generally did not produce any significant increase in crop N recovery or seed yield. However, increase in crop N recovery and seed yield in 100 kg N ha^{-1} urea treatments indicates that there was insufficient P available in the soils to maximize crop N recovery and seed yield. It appears that LSM is able to provide sufficient amounts of available P when applied annually at rates of 37,000 L ha^{-1} or higher.

At the Melfort site, the addition of supplemental S fertilizer did not significantly affect crop N recovery or seed yield in LSM treatments. Annual applications of the low rate of LSM of 37,000 L ha^{-1} supplied sufficient amounts of N and S to maximize seed yield and crop N recovery. However, large significant increases in seed yield and crop N recovery with supplemental S fertilizers were observed in the 80 kg N ha^{-1} urea treatment.

The use of a nitrification inhibitor added to LSM was effective at maintaining N in NH_4^+ form longer; however there was no significant effect on final yield, grain N or %N recovery. This may be due to the low N loss potential on prairies. Supplemental S and P fertilizer may be required with liquid swine manure. Supplemental commercial fertilizers with LSM are dependant on: the crop nutrient requirements, soil nutrient status and manure nutrient composition.

ACKNOWLEDGEMENTS

I would like to express sincere thanks to my supervisor Dr. Jeff Schoenau for his expertise, guidance, and enthusiasm. Thanks are also extended to my committee members, Dr. Diane Knight, Dr. Sukhdev Malhi, and my external examiner Dr. Terry Fonstad for you comments and suggestions.

I would like to thank Cory Fatteicher and Tom King for their invaluable assistance and direction in field sampling and laboratory analysis.

I would also like to acknowledge the financial assistance provided by Sask Pork and ADF, and the assistance of the farm cooperators (Colin Ford, Victor Hamilton, and Rick Leoppky) which were responsible for the site operation and maintenance. A thanks also goes out to the staff at the Prairie Agricultural Machinery Institute and the staff at the Melfort Agricultural Research Station.

DEDICATION

This thesis is dedicated to my loving wife, who always provided me with endless encouragement and support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

Intensification of swine operations and the need to dispose of large amounts of manure, along with increasing cost of fertilizer has led to interest in developing ways to more effectively use swine manure as a crop nutrient source. Swine manure is capable of supplying various plant nutrients, including nitrogen (N). Nitrogen often receives the greatest attention as it has the ability to greatly enhance crop production, but also may contribute to pollution when excessive amounts of manure are applied. Environmental concerns include the loss or escape of excess N from the soil through processes such as leaching, denitrification, and volatilization (Mooleki et al., 2002). Maximizing crop recovery of applied manure N will help ensure economic benefit is realized from the manure N, while at the same time minimizing risk of loss to the environment.

Availability of nutrients from liquid swine manure (LSM) can be variable depending on animal feeding, manure storage, and time of manure application. Much of the N in LSM is present as ammonium (NH_4^+) and this form can be absorbed by plant roots. Microbial transformation of NH_4^+ to nitrate (NO_3^-) in the soil is termed nitrification. Nitrification increases the risk of loss, as the NO_3^- can be readily leached and also lost through denitrification. One strategy that may improve crop recovery of manure N is the addition of a nitrification inhibitor to LSM. The recovery of applied manure N can also be affected by the balance of available N to other nutrients, as deficiencies of other nutrients can restrict yield and crop N uptake (Schoenau et al., 2000). Little work has been done to examine crop response to supplemental commercial fertilizer such as phosphorus (P) and sulfur (S) added to soils receiving LSM. It is important to document the yield and N recovery responses to supplemental commercial fertilizer, so as to permit more accurate fertilizer recommendations to be made on land receiving repeated LSM applications.

The goal of the experimental work described in this thesis was to examine possible ways of increasing the plant uptake of LSM-N applied to the soil. The goal was to use N supplied in the LSM more efficiently. Two strategies were evaluated: 1) adding a nitrification inhibitor to the manure and 2) applying supplemental P or S fertilizer to manured soils. Specifically the objectives were to:

1. determine if a nitrification inhibitor added to LSM would increase crop recovery of N supplied in LSM at the agronomic N based rate of 37,000 L ha^{-1} in a Black Chernozem at Dixon SK;
2. determine if supplemental P and S commercial fertilizer added to soil amended with LSM would increase crop recovery of N applied as LSM to a Black Chernozem at Dixon and a Dark Grey Luvisol at Melfort, respectively.

2 LITERATURE REVIEW

2.1 Manure Nitrogen: Forms and Fate

Swine manure is capable of supplying many nutrients required for crop production. Perhaps the most important nutrient supplied through land application of swine manure for plant growth is N. It is important to manage manure N effectively to ensure maximum recovery of N by the crop and minimize the impact on the environment. Manure N can be lost through processes such as volatilization, nitrification, denitrification, immobilization and leaching. It is important to accurately match N supplying power of manure with crop requirements to maximize N recovery and minimize losses. Determination of plant available N that is derived from the manure supplied can be difficult, as the distribution of manure N forms is highly variable and the rate at which organic N is mineralized is affected by many factors (Schoenau et al., 2000). In order to balance crop N requirements with manure N application it is important to determine the forms and concentrations of N in the manure. Reliable assessment of the plant available inorganic N (NH_4^+-N and NO_3^--N) in the manure is important, but there must also be some consideration of the contribution from organic N that will be mineralized throughout the growing season.

2.1.1 Manure forms

Manure N is composed of two main forms of N: NH_4^+-N (inorganic) and organic N. The majority of the inorganic N in swine manure is typically made up of NH_4^+-N (Tri-Provincial Manure Application and Use Guidelines, 2003). Nitrate is another form of inorganic N that could be present in swine manure, but generally is found in very low amounts due to the storage of liquid manure in anaerobic holding cells or lagoons (Adeli and Varco, 2001). Anaerobic conditions result in denitrification of any NO_3^- present and also inhibit any further formation of NO_3^-

through nitrification, as it is the nitrification process that converts NH_4^+ to NO_3^- is aerobic. Levels of NH_4^+ in swine manure slurries have been reported to range from 60-98% of total N present as NH_4^+-N (Adeli and Varco, 2001; Chantigny et al., 2001; Mooleki et al., 2002; Ball-Coelho et al., 2005). In a study performed by Adeli and Varco (2001) it was noted that the N present in the swine effluent consisted primarily of NH_4^+-N (84%), with negligible amounts of NO_3^--N (2.2%). The high proportion of ammoniacal N was believed to be a result of the anaerobic decomposition processes that take place in a swine manure lagoon (Adeli and Varco, 2001). Nitrification of swine manure NH_4^+-N occurs rapidly after manure application (Flowers and O'Callaghan, 1983). This can result in increased NO_3^--N levels in the soil after manure application. Increasing NO_3^--N levels shortly after manure application was observed in a field study conducted in Quebec on a loamy sand soil (Chantigny et al., 2001). Nitrification of NH_4^+ resulted in an increase of NO_3^--N content (5 g m^{-2}) in soils 7 days after swine manure application. Decreasing amounts NH_4^+-N in the soil were replaced by increasing amounts of NO_3^--N during this time. It was concluded that the increase in NO_3^--N (5 g m^{-2}) was responsible for 90% of the net NH_4^+-N disappearance (5.6 g m^{-2}) during the first 7 days after manure application. This rapid accumulation of NO_3^--N could represent a potential risk of N loss through denitrification and leaching (Chantigny et al., 2001).

Organic N is not measured directly from manure analysis but is calculated by subtracting the NH_4^+-N from the total N present in the manure (Tri-Provincial Manure Application and Use Guidelines, 2003). Total N is a measurement of all the N present in the manure, only a portion of which is typically plant available. The organic fraction of the manure must undergo decomposition (mineralization) to become plant available. Mineralization can supply appreciable amounts of N. In a Saskatchewan study pre-seeding levels of plant available N were higher than the amount of NH_4^+-N applied as swine manure the previous fall (Mooleki et al., 2002).

2.1.2 Manure N recovery

Recovery of N from animal manures can vary depending on method and rate of application. Nitrogen recovery of LSM is generally increased when the manure is injected into the soil rather than spread on the soil surface (Ball Coelho et al.,

2006; Sorensen and Amato, 2002). At high application rates the advantage of injection was decreased, with higher rates resulting in lower N recovery (Ball Coelho et al., 2006). At higher manure application rates, crop uptake (kg N ha^{-1}) of manure N generally reaches a plateau as the crop can only uptake and accumulate a finite amount of N in the grain and straw. Therefore, manure N recovery as a proportion of that applied decreased with increasing application rate (Adeli and Varco, 2001; Mooleki et al., 2002; Wen et al., 2003a). Mooleki et al. (2002) found in Saskatchewan that cumulative N use efficiency (NUE) decreased linearly with increasing rates of swine manure. Four rates of swine manure were used in the study: 0,100, 200, and 400 kg total N ha^{-1}. The highest NUE was observed in the low application rates (50-60%), while the lowest NUE was (10-30%) in the high annual application rates.

2.1.3 Volatilization

Applications of swine manure to soil surfaces can result in higher losses of N compared to injection or incorporation. Rochette et al., (2001) reported that application of LSM to the soil surface (SURF) versus a rapid incorporation of the manure (INCORP) into the top 5 cm, resulted in significant (80%) reduction of ammonia (NH_3^+) volatilization in the INCORP plots compared the SURF. Lower volatilization rates of manure with incorporation were also noted by other researchers (Chantingny et al., 2001; Dendooven et al., 1998; Hoff et al., 1981). Nitrogen losses through NH_3 volatilization were reported to account for up to 40% of swine manure N on the day of application (Morvan et al., 1997), and up to 60% of N lost within the first 11 hours of surface application (Rochette et al., 2001). In a controlled laboratory experiment, NH_3 volatilization was reduced by up to 90% by the injection of pig slurry compared to the same treatment where the LSM was applied to the soil surface (Dendooven et al., 1998).

Losses of NH_3^+-N from broadcast LSM can vary considerably with soil pH, air temperature, and air movement (wind) (Hoff et al., 1981). Increased soil pH and manure pH can result in greater NH_3^+-N losses when comparing greenhouse and field experiments (Hoff et al., 1981). During a 3.5 day period, close to 65% of the applied NH_4^+-N was volatilized from the high pH soil (7.0) and manure (7.8) in the

greenhouse, while only 14% of the applied NH_4^+-N was volatilized from the field soil that had a pH of 6.5 and manure of pH 6.4. Application method and pH of the soil and manure are important factors influencing the NH_3^+-N losses from LSM (Hoff et al., 1981).

2.1.4 Nitrification

Nitrification is the conversion of NH_4^+ into NO_3^- through microbial oxidation (Gasser, 1970). Nitrification is a two step process in which NH_4^+ is converted to nitrite (NO_2^-) and then further to NO_3^-, by *Nitrosomonas* and *Nitrobacter* bacteria, respectively. Nitrification is a microbial process, and therefore is highly dependant on the soil environmental conditions. Soil conditions that favor the nitrification process typically are favorable for agricultural plants. Several factors that influence the rate of nitrification include: supply of NH_4^+, population of nitrifying organisms, soil pH, moisture and temperature (Havlin et al., 2005). The amount and supply of available NH_4^+ with respect to the population of nitrifying organisms will play an important role on the nitrification process. Swine manure generally contains high concentrations of NH_4^+-N which is rapidly nitrified when added to aerated soils (Vallejo et al., 2005). Soil pH of 8.5 is optimum for nitrification, although the process can occur between the pH range of 4.5 to 10. When soil oxygen content is the same concentration as the above-ground atmosphere maximum nitrification will take place. Soils which have a coarse texture or that have large macropores related to aggregation can facilitate rapid gas exchange. In a study comparing the nitrogen dynamics of LSM slurry applied to a sandy loam and a clay soil, nitrification was elevated in the sandy loam soil compared to the clay soil which was attributed to enhanced aeration in the sandy loam soil (Chantigny et al., 2004). When soil moisture is at or close to field capacity (70-80% of total pore space) nitrification rates are maximized (Havlin et al., 2005). The combination of soil aeration and soil moisture are closely related in their effects on nitrification. The process of nitrification can occur over a wide range of soil temperatures (5-35ºC) with a temperature coefficient of 2 (Havlin et al., 2005). This means that a twofold increase in the nitrification rate will be seen

for every 10 ºC change in soil temperature. Maximum nitrification rates are observed between 25 to 35 ºC (Havlin et al., 2005).

2.1.5 Denitrification

Denitrification can result in large losses of manure N in soils receiving manure applications, following nitrification (McCormick et al., 1983). As soils become waterlogged and the water filled pore space surpasses 70-80%, the process of nitrification is overtaken by denitrification. When O_2 is not available anaerobic organisms acquire their O_2 from NO_2^- and NO_3^-, resulting in the release of N_2 and N_2O gases. Denitrification potential is high in agricultural fields but will only occur if anaerobic conditions are present. Denitrification can account for 70-93% of N_2O losses from fertilized and unfertilized plots after an irrigation event (Vallejo et al., 2005).

2.1.6 Leaching

Balancing N additions from LSM applications with crop uptake is crucial to minimize risk of N leaching. The LSM contains a substantial portion (30-90%) of the N in the NH_4^+ form (Schoenau et al., 2000) which is not susceptible to leaching in prairie soils. However once nitrification of the manure N occurs, the NO_3^--N that is produced can accumulate if not used by crops. This NO_3^- is subject to downward movement in the profile with percolating water. Nitrate-N is much more susceptible to leaching compared to NH_4^+-N due to its low adsorption to soil colloids. In prairie soils, clays and organic matter are negatively charged which repel anions like NO_3^-, and result in cations like NH_4^+ being sorbed.

A study by Stumborg et al. (2007) in Saskatchewan involving three different soil types receiving different rates of LSM resulted in varying levels of NO_3^- movement observed within the profile after five to seven years of manure application. When manure was applied at rates that exceeded crop N uptake and export, it resulted in a build up of NO_3^--N near the surface. Large rainfall events or irrigation can slowly move NO_3^--N down in the profile below the rooting zone. The magnitude of NO_3^--N movement through the soil is strongly influenced by soil texture, duration of rainfall, and water infiltration (Stumborg et al., 2007). Overall it

was found that when agronomic rates of LSM (37,000 L ha^{-1} yr^{-1}) were applied annually or larger rates (111,000 L ha^{-1} yr^{-1}) were applied once every 3 years, there was no significant amount of N loss evident through leaching. Only large and excessive amounts of LSM produced any significant evidence of NO_3^--N loading at the soil surface (0-60 cm) or leaching below this depth (Stumborg et al., 2007).

A six year study conducted on a loamy soil in Iowa found that applications of LSM to soils with subsurface drainage systems (tiles) can result in elevated levels of NO_3^--N in the tile water compared to soils fertilized with urea ammonium nitrate (UAN) (Bakhsh et al., 2005). Levels of NO_3^--N in the tile water from LSM was investigated and compared to NO_3^--N levels from UAN application under continuous corn, and corn-soybean rotations. It was found that there was a significantly greater flow weighted average (FWA) NO_3^--N concentration in tile water after LSM compared to UAN. Peak FWA NO_3^--N concentrations occurred at 31.8 mg L^{-1} under LSM and 15.5 g L^{-1} under UAN-applications. It should be noted that the NO_3^--N levels were observed to be significantly affected by seasonal rainfall and differences in crop growing conditions (Bakhsh et al., 2005). When the yields were averaged over the 6 years of the study under a continuous corn rotation, no differences in corn grain yield between the LSM and UAN-applications were observed. Liquid swine manure did however result in significantly higher NO_3^--N losses compared to UAN-applications (26 kg N ha^{-1} and 17 kg N ha^{-1}, respectively). Crop rotation appeared to play a role in the crop's utilization of LSM. Averaged over the 6 years of the study, there were no differences in NO_3^--N leaching losses, but there was an increase in corn grain yield observed under a corn-soybean rotation with LSM compared to UAN fertilizer (Bakhsh et al., 2005).

2.2 Nitrification Inhibitors

Nitrification inhibitors are compounds that are used to delay the bacterial oxidation of NH_4^+ to NO_2^- (Boeckx et al., 2005), which is the first step in the nitrification process. *Nitrosomonas* spp. typically oxidize the NH_4^+ to NO_2^-, and then *Nitrobacter* spp. will further oxidize the NO_2^- into NO_3^- (Gasser, 1970). Nitrification can be inhibited at either stage. If the first stage is inhibited the whole process will stop regardless if the second stage

is inhibited there can be a build up of NO_2^- which can be toxic to plants (Gasser, 1970). The use of nitrification inhibitors allows fertilizer N to be kept in the NH_4^+ form, where it is less vulnerable to N loss mechanisms such as denitrification and leaching as discussed in previous sections.

The use of nitrification inhibitors with commercial fertilizers is well documented. Gioaacchini et al. (2002) observed that the use of dicyandiamide (DCD) in conjunction with urea fertilizer was effective in keeping fertilizer derived-N as NH_4^+ compared to urea fertilizer alone. It was also noted that there was lower fertilizer derived N that was plant available when DCD was added to urea, which could be attributed to the reduced mobility of the NH_4^+ ion in the soils and its preferential immobilization by heterotrophic microflora (Gioaacchini et al., 2002). Reduced N_2O losses from crops fertilized with urea amended with nitrification inhibitors has also been observed (Boeckx et al., 2005; Shoji et al., 2001). Average emissions of N_2O in a 90 day field trial in Colorado were observed to be lower from barley plots fertilized with urea + DCD compared to urea fertilizer alone (Shoji et al., 2001). Measurements of N_2O emissions were taken at 0-20, 21-40, 41-80, and 81-90 days after fertilization (DAF). When N_2O losses were averaged over the entire experiment, the urea only fertilizer resulted in significantly higher emissions of 8.2 g N_2O-N $ha^{-1}d^{-1}$ compared to 5.2 g N_2O-N $ha^{-1}d^{-1}$ in the urea + DCD. Similar results were observed in an 80 day pot experiment using wheat (Boeckx et al., 2005). Using PVC chambers, gas samples were taken throughout the 80 day growing period and analyzed for N_2O concentration using gas chromatography. Emissions of N_2O were reduced by 22% in the treatments with urea receiving DCD compared to urea that did not receive DCD (Boeckx et al., 2005).

The use of nitrification inhibitors has not been confined to use with commercial fertilizers but has also been occasionally investigated with regards to LSM. The effectiveness of nitrapyrin [2-chloro-6 (trichloromethyl) pyridine] on controlling nitrification on soils in Indiana receiving LSM was studied by McCormick et al. (1983). Liquid swine manure was treated with a commercially available nitrapyrin product at a rate of 0 and 50 mg L^{-1} and applied at 0 and 60 t ha^{-1} (0 and 156 kg ha^{-1} of available N). The LSM was banded into the soil, and soil

samples were taken periodically to evaluate the effectiveness of the inhibitor by monitoring NH_4^+-N levels in the soil for 24 weeks. At 24 weeks nitrification was virtually complete for both the treated and untreated LSM plots. Ammonium-N in LSM bands that did not receive nitrapyrin were rapidly nitrified, and had nearly undergone complete nitrification within the first 7 weeks of the experiment. High levels of inorganic N (NH_4^+-N and NO_3^--N) remained in the untreated LSM treatment until week 7, after which there was a continuous loss of inorganic N from the soil. After this point the NH_4^+-N and NO_3^--N levels remained low for the remainder of the experiment (McCormick et al., 1983). Addition of nitrapyrin to the LSM resulted in higher levels of inorganic N throughout the experiment. Nitrification was delayed by the inhibitor for 13 weeks after LSM application. When the nitrification inhibitor was added to the LSM, no significant levels of nitrification were observed until 15 weeks after manure application (McCormick et al., 1983). It is interesting to note that during the time period when significant amounts of inorganic N was lost from the untreated LSM (between weeks 7 and 11), the study area received a substantial amount of precipitation. Increases in inorganic N losses during this time period from the untreated LSM plots could be attributed to higher rates of denitrification and leaching as the soils became water-logged. Due to the delay in nitrification in the nitrapyrin treated LSM plots, denitrification and leaching losses of NO_3^--N were minimized (McCormick et al., 1983).

Decreased levels of nitrification and leaching were observed by Vallejo et al. (2005) when using LSM treated with a nitrification inhibitor (DCD) on an irrigated soil. Three treatments of 4.9 L m^{-1} of LSM (approximately 200 kg N ha^{-1}) and one control plot also receiving 4.9 L m^{-1} of water were investigated. The LSM treatments involved: 1) surface-applied pig slurry (SPS), 2) injected pig slurry (IPS), 3) injected pig slurry + DCD (IPS + DCD), and 4) control treatment that received 4.9 L m^{-1} of water and no fertilizer (control). A rapid decline in NH_4^+-N concentration in all treatments was observed shortly after LSM application with the exception of the IPS + DCD treatment, which maintained higher NH_4^+-N concentrations than the IPS treatment between 7 and 20 days after the application (Vallejo et al., 2005). During the first 30 days of the experiment, soil NO_3^--N was

generally highest in the IPS treatment while the IPS + DCD was able to maintain NO_3^--N concentrations lower than the control during the first 20-30 days, due to the nitrification inhibitor (Vallejo et al., 2005). Leachates were collected throughout the entire experiment and were calculated as a percentage of N lost through leaching. When discounting the N leached in the control plots, the percentage of N losses through leaching was 3.3% (SPS), 9.6% (IPS) and 1.7% (IPS +DCD). It was concluded that the nitrification inhibitor was efficient in reducing the NO_3^--N losses through leaching (Vallejo et al., 2005).

Addition of nitrification inhibitors to LSM has been shown to increase corn yield (McCormick et al., 1984; Sutton et al., 1990). Corn yield increased by 21% on average with the addition of 50 mg L^{-1} of nitrapyrin to LSM rates applied at < 49 Mg ha^{-1} (McCormick et al., 1984). At higher manure application rates the nitrapyrin was not as effective because of excessive amounts of plant available N added through the LSM. In a similar study by Sutton et al. (1990), corn grain yield increased an average of 7.8% over a two year cropping season with varying rates of LSM amended with a nitrification inhibitor (nitrapyrin), compared to LSM without an inhibitor. The greatest increase in corn grain yield was observed when lower rates of LSM were applied. Grain yield effects from nitrification inhibition are the most prevalent when the rate of N applied was at or below the nutrient requirements of the crop (McCormick et al., 1984; Sutton et al., 1990).

2.3 Balanced Fertilization

Liquid swine manure can be a useful tool in supplying and maintaining fertility requirements of annual crops. Nutrient concentrations within the LSM can be variable from year to year depending on animal age, and feed material (Schoenau and Assefa, 2004). To obtain meaningful and accurate analysis of LSM nutrient composition, good manure sampling methods are required. Knowledge of typical LSM nutrient composition can be useful in designing a manure management program (Table 2.1).

Table 2.1 Typical nutrient concentrations from liquid swine manure samples in Saskatchewan.

Nutrient	Liquid hog manure (feeder hogs)	
	lb/1000 gal	kg/1000 L
Nitrogen (N)	15-50	1.5-5.0
Phosphorus (P)	1-20	0.1-2.0
Potassium (K)	8-20	0.8-2.0
Sulfur (S)	0.1-3	0.01-0.3
Copper (Cu)	0.05-0.5	0.005-0.05
Manganese (Mn)	0.05-0.5	0.005-0.05
Zinc (Zn)	0.05-1.0	0.005-0.1
Boron (B)	0.01	0.001

Source: Adapted from Schoenau et al. (2000).

Consideration must be made regarding the nutrient availability from the LSM. Some nutrients such as N, P and S may exist partly in the organic form and will need to undergo decomposition or mineralization into inorganic plant available forms. For this reason nutrients from LSM are more slowly available to plants as compared to commercial fertilizers (Schoenau et al., 2000). In a controlled environment study in Saskatchewan soils, it was observed that the availability of total N added through LSM during the year of application was around 60% of that observed with commercial urea fertilizer (Qian and Schoenau, 2000). Predictions of plant available P during the year of LSM application in prairie soils is around 50% (Tri-Provincial Manure Application and Use Guidelines, 2003). Potassium (K) contents of LSM have been found to be similar to NH_4^+-N contents, with plant availability of 90-100% in the year of application (Tri-Provincial Manure Application and Use Guidelines, 2003) (Table 2.1). Plant available S of LSM can be low, with approximately 20% of the total S in the LSM available for plant uptake in the year of application. High ratios of available N to available S in some LSM sources can result in N:S imbalances in crops that require high amounts of S, such as canola (Schoenau and Davis, 2006).

Application of LSM to meet crop N requirements can result in over application of P fertilizer, as animal manures have an average N:P ratio of 3:1, and major grain crops have a N:P ratio of 8:1 (Daniel et al., 1994). Stumborg (2005)

found that increased N and P loading occurred under drought conditions due to limited crop uptake and removal when an agronomic rate of LSM (37,000 L ha^{-1} yr^{-1}) was applied annually in Saskatchewan on a fine textured soil. Overall, it was concluded that an agronomic rate of LSM based on anticipated crop N requirements is not likely to result in elevated levels of P in the short term (Stumborg, 2005). Smith et al. (2004) observed that the use of a phytase enzyme added to the hogs diet decreased the P content relative to N in LSM which could help to lower the risk of P loading issues. The enzyme increases the efficiency of feed P utilization by monogastrics, and in turn reduces the P that is excreted in the manure (Smith et al., 2004).

Knowledge of manure nutrient concentrations, forms, behavior, and plant availability are required to optimize crop yield and nutrient recovery, while minimizing negative impacts to the environment (Schoenau and Davis, 2006). Nutrient proportions in LSM are variable and may not be able to supply the crop nutrient demands in the proper amounts, as they are not an "off the shelf" fertilizer. Achieving balanced crop fertilization using LSM may require supplementation with commercial fertilizers.

Supplemental commercial fertilizer applications made to land receiving LSM may have positive effects on nutrient recovery by overcoming a nutrient limitation, and thereby increasing the uptake of other nutrients. When application of LSM is based on N or P requirements to ensure loading does not become a problem, care must be taken that other nutrient deficiencies do not limit uptake of the N and P. Soils that typically show nutrient deficiencies, or crops with high nutrient requirements such as canola could benefit most through commercial fertilizer supplementation.

3 MATERIALS AND METHODS

3.1 Site Descriptions

3.1.1 Dixon

The Dixon field site is located at NW21-37-23-W2 in east-central Saskatchewan, about 6.5 km west of Humboldt. The field site was initiated in 1997 under a typical cereal-oilseed cropping management (Table 3.1) with no history of manure application. The soil at the Dixon site is classified as a Black Chernozem of the Cudworth association, formed on highly calcareous silty lacustrine materials that typically have a loamy surface texture (Saskatchewan Soil Survey, 1989). The land is gently sloping, slightly stony, with low susceptibility to wind and water erosion (Saskatchewan Soil Survey, 1989). Overall, the soil at the Dixon field site is of good agricultural productivity.

Table 3.1 Crop rotations for Dixon and Melfort field sites since site initiation.

	Year									
Site	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Dixon	canola	wheat	barley	canola	wheat	flax	barley	canola	wheat	flax
Melfort	-------	-------	-------	wheat	canola	oats	canola	oats	canola	barley

3.1.2 Melfort

The Melfort field site is located at SW26-44-18-W2 in north-central Saskatchewan, about 5 km south and 6.5 km east of Melfort. The field site was initiated under a typical continuous crop rotation of field crops for the region, with no history of manure application (Table 3.1). The soil is classified as a Dark Grey Luvisol of the Kamsack/Melfort association and consists of degraded black silty to clayey soils on medium to heavy glacial lacustrine deposits (Saskatchewan Soil

Survey, 1950). The soil landscape is very gently sloping with very few stones, good drainage, and low susceptibility to wind and water erosion. Overall this site represents agricultural land with good moisture supply and productivity. Sulfur deficiency has been reported as a limitation at this site (Schoenau et al., 2003).

3.2 Experimental Design

3.2.1 Dixon

The Dixon site was established in 1997 and was set up as a randomized complete block design (RCBD) as shown in Figure 3.1. The study consisted of fifteen different manure application treatments. The treatments were randomized in blocks 2, 3 and 4, while treatments in block 1 were consecutive for demonstration purposes. Low levels of P in the LSM raised questions regarding the possibility of using a commercial P fertilizer to maximize crop yield. Starting in 2002 there has been annual applications of 6.5 kg P ha^{-1} (as monoammonium phosphate) treatment banded at the south end of blocks one and two, and the north end of blocks three and four. The plot size for the LSM plots are 30.5-m by 3.05-m, and the band of supplemental P fertilizer is 3.05-m by 3.05-m. Check plots at the Dixon and Melfort site are disturbed check plots where the coulters are moved through the soil but no LSM or commercial fertilizer is added.

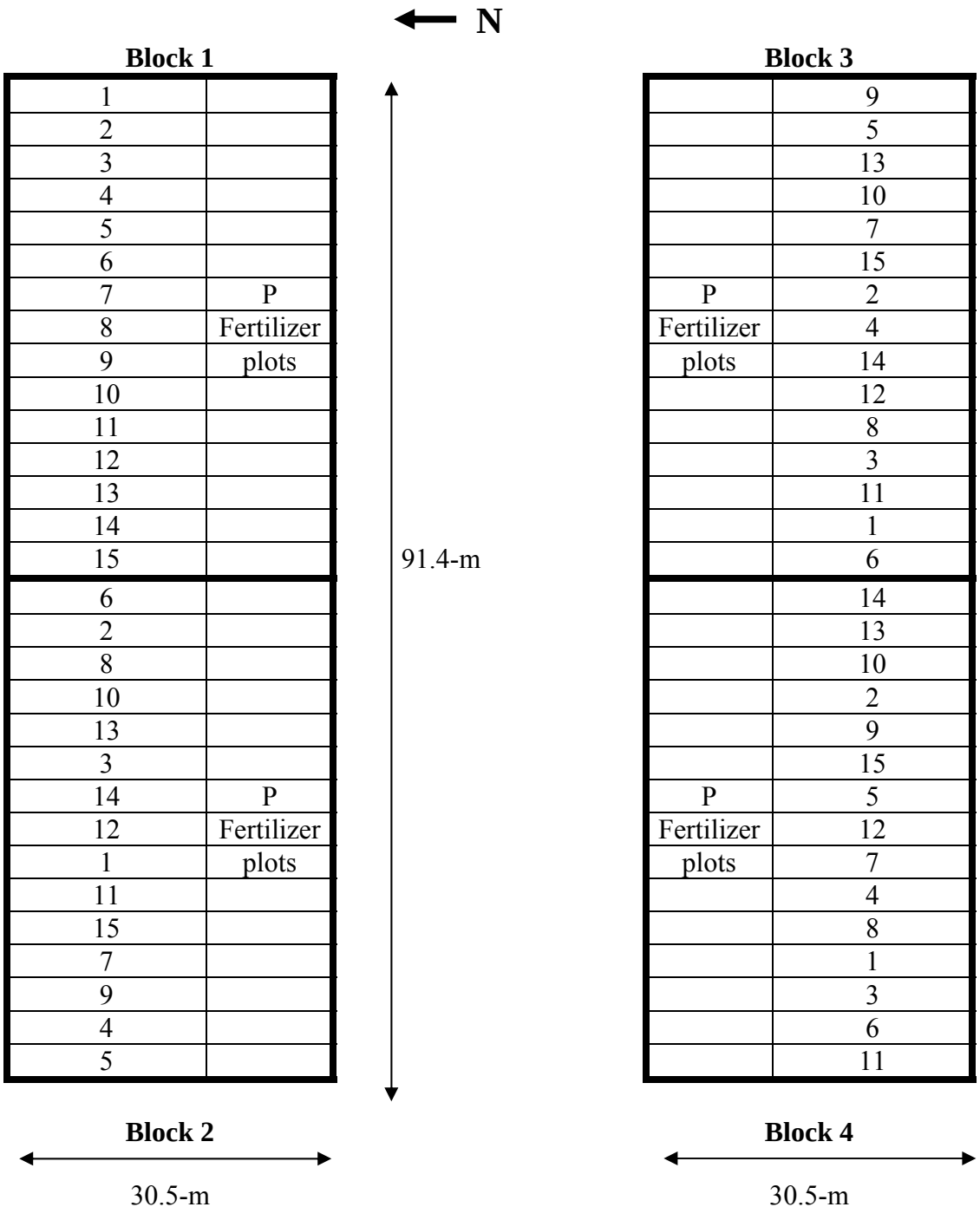

Figure 3.1 Dixon liquid swine manure site layout. (not drawn to scale).

Manure was applied at the Dixon and Melfort field sites using a liquid manure injector truck from the Prairie Agricultural Machinery Institute (PAMI, Humbolt, SK) (Figure 3.2). Manure was pumped into the liquid manure injector truck from an unagitated, single cell, earthen manure storage unit.

Figure 3.2 Prairie Agricultural Machinery Institute liquid manure injector truck used to apply liquid swine manure at the Dixon and Melfort sites.

The LSM was injected into the soil at an average depth of 10 cm using low disturbance Bourgault disc openers. Dixon and Melfort field sites received LSM from the same earthen storage unit. Liquid swine manure was applied in the previous fall for the 2004 and 2006 field seasons for Dixon and Melfort. Due to early freezing of the soil in the fall, the LSM was applied in the spring of 2005 for the 2005 field season at both field sites. A complete list of LSM treatments for the Dixon field site is shown in Table 3.2. Dates of LSM application and nutrient composition are shown in appendix A.

Table 3.2 Description of liquid swine manure treatment applications at Dixon since 1997.

Treatment #	Description
1	Control - No injector pass
2	Control – Injector pass @ 30 cm spacing
3	1X† - LSM injector pass @ 30 cm spacing applied once every 3 years
4	1X - LSM injector pass @ 30 cm spacing applied every year
5	2X‡ - LSM injector pass @ 30 cm spacing applied once every 3 years
6	2X - LSM injector pass @ 30 cm spacing applied every first and third year
7	2X - LSM injector pass @ 30 cm spacing applied every year
8	4X§ - LSM injector pass @ 30 cm spacing applied once every 3 years
9	4X - LSM injector pass @ 30 cm spacing applied every year
10	1X¶ - LSM injector pass @ 30cm spacing applied every year
11	1X - LSM injector pass @ 30 cm spacing applied every year
12	1X - LSM broadcast and incorporated every year
13	1X - banded urea fertilizer applied every year
14	2X - banded urea fertilizer applied every year
15	4X - banded urea fertilizer applied every year

† 1X refers to an agronomic rate of LSM or urea, equal to 37,000 L ha^{-1} (~100 kg total N) and 50 kg N ha^{-1}, respectively.
‡ 2X refers to twice the agronomic rate of LSM or urea, equal to 74,000 L ha^{-1} and 100 kg N ha^{-1}, respectively.
§ 4X refers to four times the agronomic rate of LSM or urea, equal to 148,000 L ha^{-1} and 200 kg N ha^{-1}, respectively.
¶ refers to the addition of Super N Concentrate nitrification inhibitor at 0.275 mL kg^{-1} to the LSM (in 2005 and 2006).

In the spring of 2005 when manure treatments were applied, and again in the fall of 2005 when manure was applied for the 2006 field season, a nitrification inhibitor was added to the LSM in treatment #10. The nitrification inhibitor used in the experiment was dicyandiamide (DCD). The commercial product (Super N Concentrate) contained both a nitrification and urease inhibitor, as a product containing nitrification inhibitor alone was not commercially available in Canada at that time. It was anticipated that the majority, if not all of the inhibition, would be from the DCD, as all or most of the urea in the manure would have already undergone hydrolysis by the time of manure application. It has been shown that 30-90% of the N in LSM is in the NH_4^+ form (Schoenau et al., 2000). The product was added to the liquid manure in the applicator tank of the PAMI manure injection truck at a rate of 0.275 mL kg^{-1} of liquid manure, and agitated for several minutes prior to application. The LSM treatment that received the nitrification inhibitor was

the last treatment to have manure applied, to ensure there would be no cross contamination with any other treatments.

3.2.2 Melfort

The Melfort site was established in 2000 and was set up as a RCBD (Figure 3.3). The study consisted of five manure application treatments replicated in four blocks (Table 3.3). Treatments were laid out consecutively in block 1 for demonstration purposes, but were randomized in blocks 2, 3 and 4. After this site had been established in 2000, S deficiencies were observed. In 2002 sub-treatments of potassium sulfate (K_2SO_4) and elemental sulfur (S^o) were applied as spring broadcasting of commercial fertilizer in strips along the east end of all the treatments. The S fertilizer products were broadcast at 40 kg S ha^{-1} beginning in 2002 and repeated every three years, with an application made again in 2005. Melfort manure treatment plots were 30.5-m by 3.05-m, and sub-treatment plots were 3.05-m by 3.05-m.

3.3 Field Sampling

3.3.1 Growing season assessment of soil mineral N and plant total N (Dixon 2005, 2006)

Field sampling was conducted over the 2005 and 2006 growing season using the same procedures both years. Samples of soil, plant material, and PRS^{TM} probe measurements of soil N were made every two weeks in treatments #2, 4, and 10 (Table 3.2) to monitor N dynamics as affected by the addition of the nitrification inhibitor. Prior to seeding and manure application in 2005 and prior to seeding in 2006, soil samples were taken from treatments 2, 4, and 10 at 0-15 cm and 15-30 cm depths in 2005, and also including the 30-60 cm depth increment in 2006 to provide information on soil profile N content. Sampling to 60 cm was attempted in the spring of 2005 but due to subsoil frost, samples to this depth could not be obtained before manure application. Four samples were taken per plot using a hydraulic punch, and the soil cores were bulked to form a single sample. All samples were air dried at room temperature and passed through a 2 mm sieve prior to laboratory analysis.

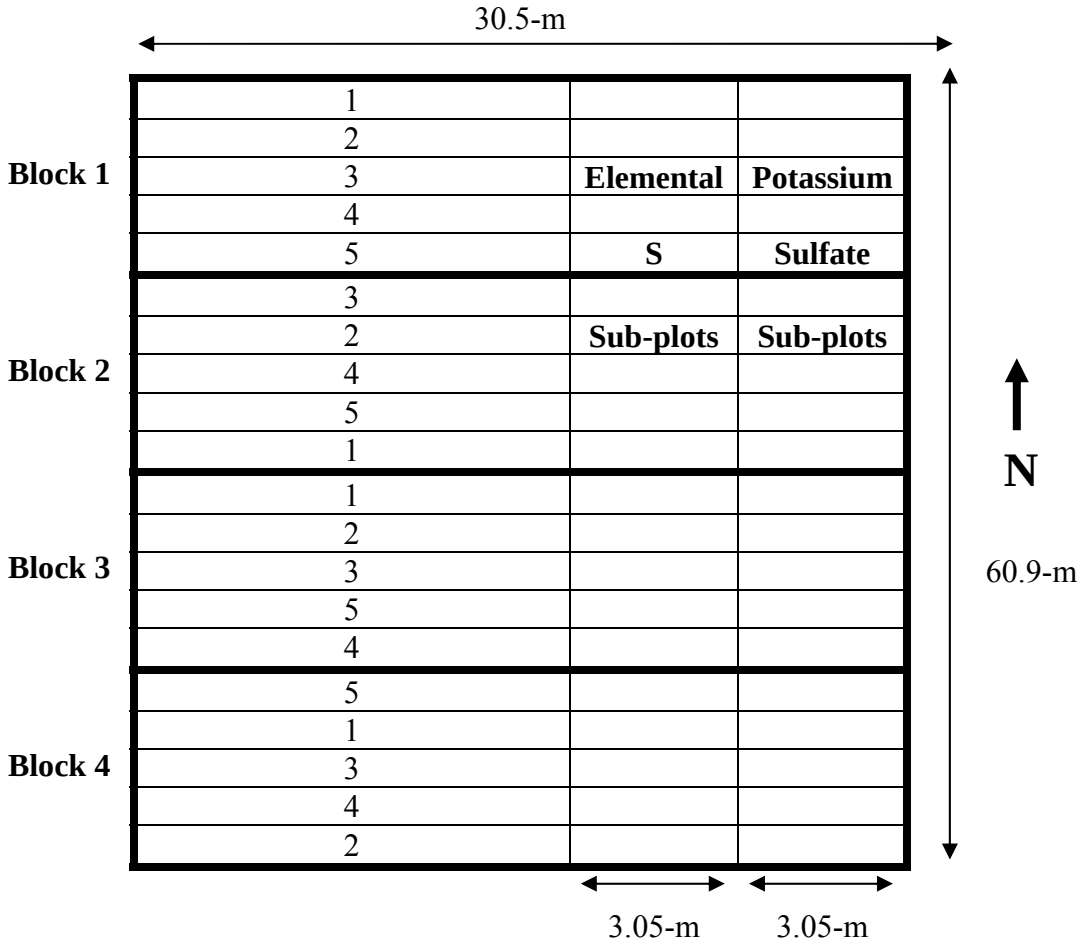

Figure 3.3 Melfort liquid swine manure site layout (not drawn to scale).

Table 3.3 Description of Melfort liquid swine manure treatment applications since 2000.

Treatment #	Description
1	Check with injector pass
2	1X† - LSM injected every year
3	2X‡ - LSM injected once every two years
4	3X§ - LSM injected once every three years
5	1X† - Urea applied every year

† 1X refers to an agronomic rate of LSM or urea, equal to 37,000 L ha^{-1} (~100 kg total N) and 80 kg N ha^{-1}, respectively.

‡ 2X refers to twice the agronomic rate of LSM, equal to 74,000 L ha^{-1}.

§ 3X refers to three times the agronomic rate of LSM, equal to 111,000 L ha^{-1}.

Throughout the growing season two soil samples per plot were taken to a depth of 0-15 cm every two weeks using a dutch auger (Table 3.4). Two spring wheat plant samples (10 cm^2) per plot were taken in 2005, and three flax plant samples (10 cm^2) per plot were taken in 2006. Three samples were taken in 2006 in an effort to reduce sampling error as the flax crop was seeded by a broadcast and incorporation method rather than in seed rows as was the spring wheat in 2005.

Table 3.4 Sampling dates for the 2005 and 2006 field seasons at Dixon. Crop was spring wheat in 2005 and flax in 2006.

2005			2006		
Soil sample	**Plant sample**	**PRS™ probe**	**Soil sample**	**Plant sample**	**PRS™ probe**
May 23	nd†	nd	May 31	nd	nd
June 6	June 6	June 6	June 14	June 14	June 14
June 20	June 20	June 20	June 28	June 28	June 28
July 4	July 4	July 4	July 12	July 12	July 12
July 18	July 18	July 18	July 26	July 26	July 26
nd	July 25	nd	August 9	August 9	August 9
August 1	August 1	August 1	nd	nd	August 23

† denotes no samples were taken.

After the crop had been seeded, four PVC cores were randomly inserted into the soil in treatments 2, 4 and 10 in all four blocks (Figure 3.4). One anion and one cation PRS™ probe was placed in each of the PVC cores to exclude plant root competition for nutrients. Anion and cation PRS™ probes were used to measure NO_3^- and NH_4^+ supply rates, respectively over a two week time period. The probes were retrieved every two weeks and new probes were placed into the same slots in the soil. Probes remained in the soil until the crop had reached the dough stage.

Figure 3.4 PVC core with anion and cation PRS^{TM} probe.

Plant samples were taken from a one meter square area at harvest from all swine manure plots by hand using a sickle and placed in cotton bags (Table 3.5). Harvest samples were dried and threshed for grain and straw yield, and analyzed for N concentration.

Table 3.5 Harvest dates for Dixon and Melfort for 2004, 2005 and 2006.

Site	2004	2005	2006
Dixon	August 27 (canola)	August 16 (wheat)	September 5 (flax)
Melfort	August 31 (oat)	August 11 (canola)	August 16 (barley)

3.3.2 Crop, manure and soil sampling (Dixon and Melfort 2004, 2005, and 2006)

In the fall of 2004, 2005, and 2006 plant samples were collected at maturity. Each plot was sampled using a 1m^2 quadrat placed near the location where soil samples were taken. Plants were harvested close to ground level by hand using a sickle, placed in cotton bags, and air-dried. Once the crop was dry, plant material

was weighed to obtain biomass yields. After the crop had been threshed, the grain was cleaned and weighed to determine grain yield.

Manure samples were collected for the Dixon and Melfort sites in 2004, 2005 and 2006. Samples were taken during manure application, chilled to 4˚C, and then frozen at -20˚C until laboratory analysis. All LSM application rates are expressed on a wet weight basis (Table 3.6).

Table 3.6 Average rates (kg ha^{-1}) of N, P, and S added as liquid swine manure at the 37,000 L ha^{-1} (3300 gpa) rate based on long term manure analysis.

Total N	Total P	Total S
----------	kg ha^{-1}	----------
75-100	5-10	7-10

Fall soil sampling was performed at Dixon and Melfort in 2004, 2005 and 2006. Fall soil samples at Dixon in 2004 were only taken on treatments 2, 4, 5, 7, 8, 9, and 14 in the minus P LSM plots, and the 0-30, 30-60, 60-90, 90-120, and 120-150 cm depths were sampled. In the LSM + P plots, soil samples were collected from treatments 2, 4, 7, 9, and 14 to the 0-30 cm depth. The 2005 fall soil samples from the Dixon site included all treatments (LSM and LSM+P) in depth increments of 0-30, and 30-60 cm. The 2006 fall soil samples consisted of all treatments (LSM and LSM+P) in depth increments of 0-15, 15-30, and 30-60 cm.

Soil samples from Melfort in 2004 were taken in depth increments of 0-30, 30-60, 60-90, 90-120, 120-150 cm in treatments 1, 2, 4, and 5. These soil samples were taken in the LSM and LSM +K_2SO_4 (potassium sulfate) plots only. Samples taken in 2005 include 0-30, and 30-60 cm depth increments in all treatments. Samples taken in 2006 at Melfort were 0-15, 15-30, 30-60, and 60-120 cm depths for LSM and LSM+ K_2SO_4 plots, and 0-30 cm and 30-60 cm depths in the LSM+ elemental S sub-treatments.

3.4 Weather Data

Weather data from the functioning weather station closest to the Dixon and Melfort sites were collected online from the Meteorological Service of Canada

(Environment Canada). Mean monthly temperature, precipitation for the 2004, 2005 and 2006 growing season (May to August) and long-term averages are provided in Table 3.7. Weather data for the Melfort site was collected from the Melfort weather station (Latitude 52º 49´ N, Longitude 104º 36´ W). Weather data for the Dixon site was collected from the Muenster weather station (Latitude 52º 19´ N, Longitude 105º 0´ W), because the Humboldt station was discontinued in July 2005.

Table 3.7 Dixon and Melfort field site mean monthly temperature, precipitation, for 2004, 2005, 2006 growing season (May-August) and long term averages.

		Dixon (Muenster Station)		Melfort	
Year	**Month**	**Mean Temperature (ºC)**	**Precipitation (mm)**	**Mean Temperature (ºC)**	**Precipitation (mm)**
2004	May	7.5	39.7	6.9	34.1
	June	13.2	66.0	12.7	66.0
	July	17.4	53.5	16.5	56.4
	August	14.1	80.0	13.5	54.0
2005	May	9.4	51.8	9.1	36.8
	June	14.8	133.8	13.9	165.4
	July	18.1	44.5	17.1	70.0
	August	15.3	124.6	14.5	99.4
2006	May	10.8	88.5	11.1	63.0
	June	16.9	123.1	16.7	73.6
	July	19.8	49.4	18.3	38.6
	August	17.7	54.9	17.1	45.4
Long-Term (1971–2000)	May	10.8	44.8	10.8	45.6
	June	15.3	76.5	15.7	65.8
	July	17.4	70.6	17.4	75.7
	August	16.7	47.9	16.4	56.8

3.5 Analytical Methods

3.5.1 Soil analysis

Analysis for NO_3^- and NH_4^+ concentrations in soil samples taken in the spring, biweekly during the growing season, and in the fall were conducted using the 2*M* KCL method. The procedure was conducted according to Keeney and

Nelson (1982), where 50 mL of 2*M* KCL was added to 5 g soil in plastic extraction bottles. The bottles were then put on a rotary shaker for one hour at 142 rpm. The solution was then filtered into vials using Whatman® # 454 filter paper. The vials were capped and stored at 4˚C until they were analyzed for NO_3^- and NH_4^+ using a Technicon Autoanalyzer II.

Analysis of soil pH and electrical conductivity (EC) were made on fall soil samples following the techniques of Hendershot and Lalande (1993), and Janzen (1993) respectively. A total of 20 g of soil was weighed into plastic bottles, and then 40 mL of distilled water was added to each bottle. The bottles were then shaken for 20 min. at 142 RPM, and then let stand for two hours. The 2:1 distilled water to soil suspension was then filtered into vials using Whatman® No. 1 filter paper. The filtrate was then analyzed for pH using a Beckman 50 meter, and EC using a Horba ES-12 conductivity meter.

Labile P concentrations were determined on soil samples collected in the fall of 2004, 2005, and 2006 using the Modified Kelowna (MK) method as outlined by Qian et al. (1994), with a few modifications. The extractant was prepared by combining 0.25 *M* HOAc, 0.25 *M* NH_4OAc, and 0.015 *M* NH_4F with a measured pH of 4.9. Soil was weighed (3 g) into 100 mL plastic bottles, and 30 mL of the MK extractant was dispensed into the plastic bottles. The bottles were shaken at 200 rpm for 5 min. and then filtered through Whatman® # 454 filter paper into 7 Dram vials. Samples were stored at 4˚C until they could be colorimetrically analyzed using a Technicon Autoanalyzer II.

Analysis for sulfate was conducted using a 0.01 *M* calcium chloride ($CaCl_2$) extraction on the soil samples taken at the Melfort site following the techniques of Kowalenko (1993). A 0.01 *M* $CaCl_2$ extractant was prepared by dissolving 1.11 g of $CaCl_2$ into 1 L of distilled water. Soil samples (20 g) were weighed into plastic extraction bottles and then 40 mL of the 0.01 *M* $CaCl_2$ extractant was added to the soil. This created a 1:2 soil to extractant ratio which was shaken for 30 min. on a rotary shaker at 142 rpm. The solution was then filtered through a VWR 454 filter paper into a 7 dram vial. Vials were capped and stored in a fridge until analysis for sulfate on a Technicon Autoanalyzer II.

3.5.2 Manure and plant analysis

To determine N concentrations of LSM and plant samples a standard H_2SO_4-H_2O_2 digestion was conducted (Thomas et al., 1967). For LSM an approximate wet weight of 0.25 g, and for plant material 0.25 g of dried material was used. The sample was weighed and placed into 75 mL digestion tubes, and then 5 mL of concentrated sulfuric acid was added to each tube. The tubes were vortexed and placed on a block digester at 360˚C for 20 min. Then 0.5 mL of 30% (vol vol^{-1}) H_2O_2 was added to the tubes, vortexed again and heated at 360˚C for another 30 min. on the digester block. After 30 min. the tubes were removed, allowed to cool and then another 0.5 mL of H_2O_2 was added to each tube. The addition of H_2O_2, heating and cooling process was repeated five more times. For the last heating cycle the tubes were left on the digestion block for 1 hour instead of 30 min. to completely remove the remaining H_2O_2. After the final heating, the tubes were allowed to cool for approximately 30 min., and were brought up to volume (75 mL) with deionized water. The tubes were then shaken and then a sub-sample was transferred into 50 mL plastic vials until further analysis. The digest coverts all of the N from the plant and manure into NH_4^+. The NH_4^+ concentrations were colorimetrically determined with a Technicon Autoanalyzer II (Tarrytown, NY). Total plant N uptake was determined by multiplying the grain and straw concentrations by the grain and straw yield.

Grain and straw harvest samples from Melfort were analyzed for total N using a Leco CNS 2000 Elemental Analyzer. Samples were weighed (0.25 g) into ceramic combustion boats, and combusted at 1100˚C.

3.5.3 PRS probe analysis

Bioavailable NO_3^- and NH_4^+ fluxes in situ (µg N sorbed per cm^{-2} of membrane over two weeks) were determined throughout the growing season of 2005 and 2006 using plant root simulator (PRS^{TM}) probes (ion exchange resin membranes) according to the procedures outlined in Qian and Schoenau (2002). The anion PRS^{TM} probes were initially soaked in distilled water for 24 hrs. The probes were then soaked in 0.5 *M* $NaHCO_3$ for 2 hrs., which saturated the exchange

sites with bicarbonate as the counter ion. This process was repeated 4 times for a total soaking time of 8 hrs. After the final soak the probes were washed twice with distilled water and stored in distilled water until time of insertion into the soil. Cation PRS^{TM} probes were also soaked in distilled water for 24 hrs before undergoing the charging process. The cation probes were soaked in 0.5 *M* HCL for 2-4 hrs which allowed the exchange sites to be saturated with H^+ ions. The cation probes were then washed twice with distilled water and stored in distilled water until use.

After the probes were removed from the soil they were placed in Ziploc^{TM} bags for transport back to the lab for the extraction procedure. The probes were washed thoroughly with distilled water to remove all soil particles from the probe and membrane surfaces, and then placed in new plastic Ziploc^{TM} bags. The probes were then eluted with 20 mL of 0.5 *M* HCL, and let stand 1 h. This allowed all the sorbed ions on the membrane surface to be released into the solution. The elutant was then placed in 7 dram plastic vials and stored at 4˚C until it was colorimetrically analyzed for NO_3^- and NH_4^+ using the Technicon Autoanalyzer II.

3.6 Statistical Analysis

The experimental design of the Dixon and Melfort field site was a Randomized Complete Block Design (RCBD). Mean separation statistical comparisons were conducted using least significant difference (LSD) from a standard analysis of variance technique at $P \leq 0.10$. All LSD calculations were conducted using the GLM procedure (SAS Institute Inc., 1985).

4 RESULTS AND DISCUSSION

4.1 Effects of Nitrification Inhibitor on Soil Mineral N and Crop Total N Recovery of Swine Manure

4.1.1 2005 soil mineral N

The effects of addition of a nitrification inhibitor (DCD) to LSM on early season N dynamics was evaluated at Dixon by taking biweekly soil, plant, and PRS^{TM} probe measurements. Concentration of NH_4^+-N and NO_3^--N in the soil, NH_4^+-N and NO_3^--N supply rates (PRS^{TM} probes) and N uptake and recovery by the wheat crop in the early season and at harvest allowed for performance of the nitrification inhibitor in conserving soil N and increasing recovery to be assessed. Nutrient analysis and application dates of LSM used in the 2004, 2005 and 2006 field seasons can be found in Appendix A.

Due to an early freeze up in the fall of 2004, LSM was not applied until the spring of 2005. No differences in soil NH_4^+-N were observed to a depth of 30 cm. Amounts of NO_3^--N in the two manured treatments (15-30 cm) were elevated compared to the 0 L ha^{-1} (unfertilized and un-manured control) but were not different from one another (Table 4.1).

Table 4.1 Pre-seeding and pre-LSM application soil NH_4^+-N and NO_3^--N levels at Dixon, SK on April 21, 2005.

	NH_4^+-N		NO_3^--N	
Treatment	**0-15 cm**	**15-30 cm**	**0-15 cm**	**15-30 cm**
	----------kg N ha^{-1}----------			
0 L ha^{-1} yr^{-1}	2.30	2.30	6.93	1.44
37,000 L ha^{-1} yr^{-1}	2.78	2.65	10.58	5.70
37,000 L ha^{-1} yr^{-1}†	2.73	3.35	10.35	4.60
$LSD_{(0.10)}$	NS‡	NS	NS	1.89

† denotes addition of a nitrification inhibitor at 0.275 mL kg^{-1}.
‡ Not significant at $\alpha = 0.10$.

Biweekly soil samples were taken from the 0 L ha^{-1} yr^{-1}, 37,000 L ha^{-1}, and 37,000 L ha^{-1} + nitrification inhibitor and analyzed for NH_4^+-N (Table 4.2) and NO_3^--N amounts (Table 4.3). The amount of NH_4^+-N was higher in the treatment with added nitrification inhibitor during the first sampling period of the growing season. After the first sampling period, no differences in NH_4^+-N amounts were observed for the remainder of the growing season. This is consistent with the findings of Vallejo et al. (2005), where amounts of NH_4^+-N declined rapidly after manure application without the use of a nitrification inhibitor. When a nitrification inhibitor was added to the LSM, higher amounts of NH_4^+-N were maintained for 7 to 20 days compared to LSM without a nitrification inhibitor.

Table 4.2 Amount of NH_4^+-N in 0-15 cm soil samples taken throughout the 2005 growing season at Dixon, SK.

	Sampling dates					
Treatment	**May 26**	**June 6**	**June 20**	**July 4**	**July 18**	**August 1**
	----------kg N ha^{-1}----------					
0 L ha^{-1} yr^{-1}	10.45	9.00	8.65	12.15	8.95	8.40
37,000 L ha^{-1} yr^{-1}	11.90	11.80	8.25	12.80	9.20	9.85
37,000 L ha^{-1} yr^{-1}†	63.80	10.20	8.45	11.80	8.55	9.70
$LSD_{(0.10)}$	28.50	NS‡	NS	NS	NS	NS

† denotes addition of a nitrification inhibitor at 0.275 mL kg^{-1}.
‡ Not significant at $\alpha = 0.10$.

As expected, the amount of soil NO_3^--N was higher in the LSM treatment without the inhibitor compared to the treatment with the inhibitor early in the growing season (Table 4.3). The mean NO_3^--N levels in the 37,000 L ha^{-1} treatment tended to be slightly higher than the 37,000 L ha^{-1} + nitrification inhibitor treatment for the remainder of the growing season. Higher NH_4^+-N and lower NO_3^--N amounts during the first sampling period in the LSM treatment receiving the inhibitor suggests that the nitrification inhibitor is effective in maintaining the manure N in the NH_4^+ form early in the growing season. Vallejo et al. (2005) observed that LSM treated with a nitrification inhibitor had lower amounts of NO_3^--N than the control for the first 20-30 days after manure application. The amount of NO_3^--N in LSM treatments at the Dixon field site was never lower than the control (0 L ha^{-1}) treatment during the 2005 field season in the current study. Overall

higher amounts of total inorganic N ($NH_4^+ + NO_3^-$) was observed in the 37,000 L ha^{-1} treatment compared to the 37,000 L ha^{-1} + nitrification inhibitor treatment for all sampling dates with the exception of June 20. Lower amounts of total inorganic N in the 37,000 L ha^{-1} + nitrification inhibitor could be a result of the nitrification inhibitor slowing the rate of N mineralization from the soil, as well as inhibiting the nitrification process (Malhi and Nyborg, 1982; Malhi and Nyborg, 1983).

Table 4.3 Amount of NO_3^--N in 0-15 cm soil samples taken throughout the 2005 growing season at Dixon, SK.

	Sampling dates					
Treatment	**May 26**	**June 6**	**June 20**	**July 4**	**July 18**	**August 1**
	----------kg N ha^{-1}----------					
0 L ha^{-1} yr^{-1}	20.75	15.15	12.90	11.10	9.35	7.50
37,000 L ha^{-1} yr^{-1}	133.35	28.20	18.10	15.35	15.60	9.50
37,000 L ha^{-1} yr^{-1}†	45.00	27.45	20.10	13.65	10.80	9.00
$LSD_{(0.10)}$	20.78	NS‡	NS	NS	NS	NS

† denotes addition of a nitrification inhibitor at 0.275 mL kg^{-1}.
‡ Not significant at $\alpha = 0.10$.

The LSM treatment that received the nitrification inhibitor was able to supply higher amounts of N in the NH_4^+ form early in the growing season, as compared to the treatment that did not receive the inhibitor (Table 4.4). Higher NH_4^+-N supply rates from LSM treated with the nitrification inhibitor also indicated that the inhibitor was effective in keeping the N in the NH_4^+ form longer, by inhibiting the conversion of NH_4^+ into NO_3^-.

The NO_3^--N supply rates measured in field were consistent with the inhibitor reducing the rate of conversion of NH_4^+ to NO_3^- (Table 4.5). Although not always significant, the treatment that did not receive the nitrification inhibitor did have higher NO_3^--N supply rates over the five two-week time periods. The amount and supply rates of NH_4^+-N and NO_3^--N measured in the field in 2005 indicate that the nitrification inhibitor is inhibiting the process for approximately the first 30 days.

Table 4.4 Ammonium-N supply rates measured in-field at Dixon, SK in 2005 for control, and injected LSM without and with added nitrification inhibitor.

	Sampling dates				
Treatment	**June 6**	**June 20**	**July 4**	**July 18**	**August 1**
	----------μg N cm^{-2}----------				
0 L ha^{-1} yr^{-1}	0.06	0.08	0.21	0.59	0.48
37,000 L ha^{-1} yr^{-1}	0.05	0.04	0.23	0.41	0.46
37,000 L ha^{-1} yr^{-1}†	0.58	0.39	0.22	0.44	0.56
$LSD_{(0.10)}$	0.28	NS‡	NS	0.13	NS

† denotes addition of a nitrification inhibitor at 0.275 mL kg^{-1}.
‡ Not significant at α = 0.10.

Table 4.5 Nitrate-N supply rates measured in-field at Dixon, SK in 2005 for control, and injected LSM without and with added nitrification inhibitor.

	Sampling dates				
Treatment	**June 6**	**June 20**	**July 4**	**July 18**	**August 1**
	----------μg N cm^{-2}----------				
0 L ha^{-1} yr^{-1}	7.5	9.2	7.4	0.7	1.5
37,000 L ha^{-1} yr^{-1}	14.8	18.4	12.9	8.5	6.8
37,000 L ha^{-1} yr^{-1}†	12.2	14.7	11.2	6.2	5.5
$LSD_{(0.10)}$	3.1	3.3	NS‡	2.6	NS

† denotes addition of a nitrification inhibitor at 0.275 mL kg^{-1}.
‡ Not significant at α = 0.10.

4.1.2 2005 plant total N

There were no significant differences in wheat biomass production over the growing season between the manure treatments until the last sampling period on August 1 (Figure 4.1). The higher biomass production during the last sampling period may be related to the addition of the nitrification inhibitor to the LSM resulting in greater N availability and improved N content.

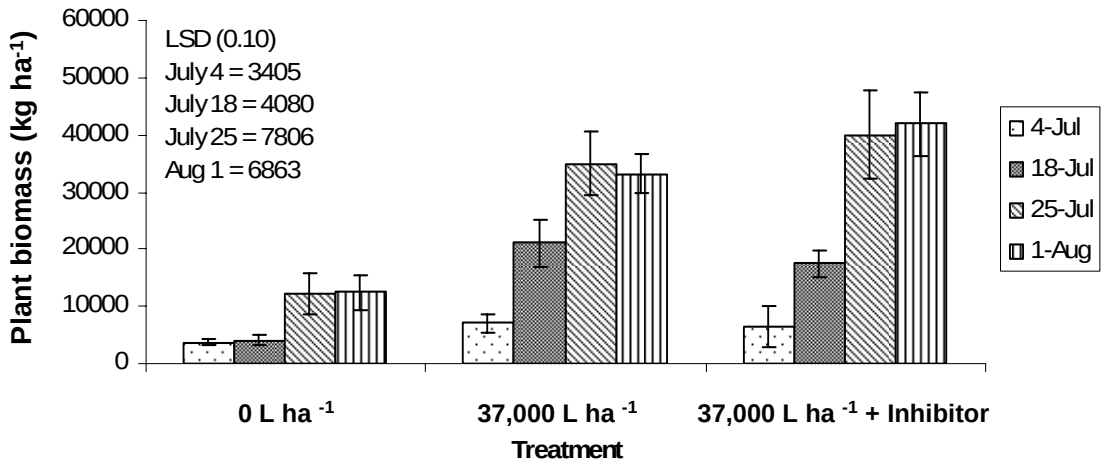

Figure 4.1 Early season biomass (kg ha^{-1}) of wheat at Dixon, SK field site in 2005.

Nitrogen uptake was calculated by multiplying the N concentration in the biomass samples by the biomass yield for each measurement made throughout the growing season. The data was then normalized to make the N uptake of the unfertilized control equal to 100%. The N uptake in the 37,000 L ha^{-1}, and 37,000 L ha^{-1} + nitrification inhibitor treatments are relative to the uptake of the unfertilized control for their respective sampling dates (Figure 4.2). No significant effects on N uptake were observed between manure treatments with the exception of July 25 sampling date, where slightly, but significantly, greater uptake was observed in the manure plus nitrification inhibitor treatment. The increase in N uptake could reflect some effect of the nitrification inhibitor in conserving more N and increasing available N early on in the season. This, in turn, may have been responsible for the higher biomass yield in the August 1 measurement.

No differences in final N uptake, seed yield, or percent N recovery were observed in the 2005 field season between the 37,000 L ha^{-1} and the 37,000 L ha^{-1} + Inhibitor treatments (Table 4.6).

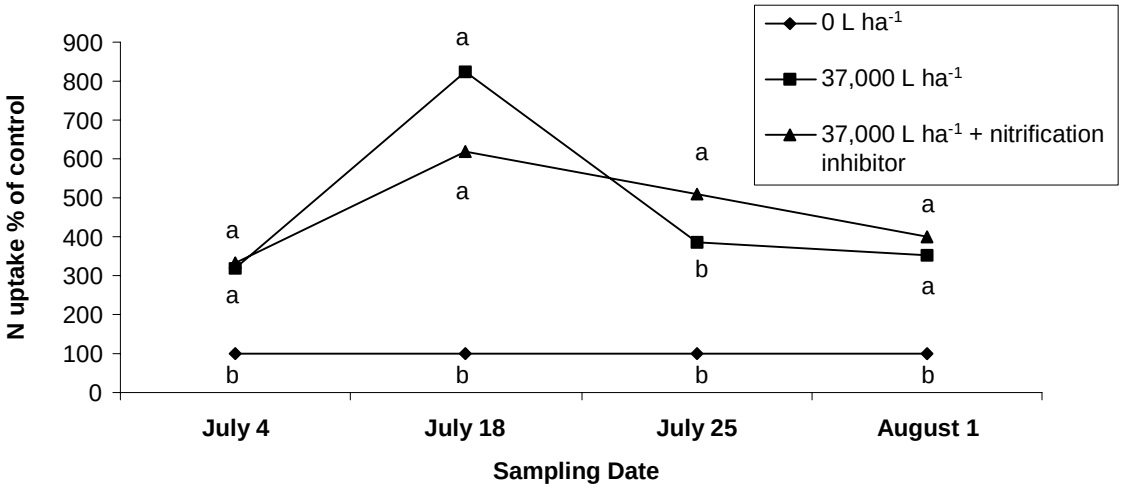

Figure 4.2 Growing season N uptake in wheat biomass at Dixon, SK in 2005 expressed as percentage of uptake in unfertilized control.

Table 4.6 Harvest N uptake, seed yield, and percent recovery of N in wheat at maturity in 2005 at Dixon, SK.

	Treatment			
	0 L ha^{-1} yr^{-1}	**37,000 L ha^{-1} yr^{-1}**	**37,000 L ha^{-1} yr^{-1}†**	**LSD$_{(0.10)}$**
N uptake ‡	18.7 (b)	80.2 (a)	74.8 (a)	15.7
Seed yield ‡	1094 (b)	3359 (a)	3110 (a)	588
% N recovery	NA	67.0 (a)	61.0 (a)	12.8

† denotes addition of a nitrification inhibitor at 0.275 mL kg^{-1}.
‡ N uptake and seed yield are reported as kg ha^{-1}.
Values in a row following same letter are not significantly different ($\alpha = 0.10$).

The addition of a nitrification inhibitor to LSM was effective in maintaining the N in the NH_4^+ form early in the growing season compared to LSM which had not received the inhibitor. These findings agree with a study that used the nitrification inhibitor dicyandiamide (DCD) with urea fertilizer (Gioacchini et al., 2002), where the use of a nitrification inhibitor maintained N as NH_4^+ for a longer time compared to untreated urea fertilizer. Vallejo et al. (2005) also reported soil NH_4^+ concentrations declined less rapidly in LSM treatments that received a nitrification inhibitor. Use of nitrification inhibitors has been shown to retard N mineralization resulting in less N available for plant uptake (Malhi and Nyborg, 1982; Malhi and Nyborg, 1983). Overall the nitrification inhibitor added to the spring applied LSM appeared to be effective in maintaining manure N in the NH_4^+

form longer in the early part of the growing season. However, the net effect on final crop yield, and %N recovery was minimal. Combined with slowed mineralization of soil N due to the nitrification inhibitor (Malhi and Nyborg, 1982; Malhi and Nyborg, 1983), these results may also reflect the overall lower loss potential for NO_3^- in these soils under the conditions of the study compared to previously reported work in other locations.

4.1.3 2006 soil mineral N

In 2006, flax was grown on the Dixon field site, and LSM treatments were applied in the fall (October) of 2005. Spring pre-seeding (April 26) soil samples were taken at 0-15, 15-30, and 30-60 cm and analyzed for NH_4^+ and NO_3^- to monitor soil N levels as affected by the application of LSM with and without the addition of a nitrification inhibitor the previous fall (Table 4.7). Levels of NH_4^+-N were higher in the treatment with the inhibitor in the 0-15 cm depth, which could be attributed to the inhibitor keeping the manure N in the NH_4^+ form longer. Differences in NO_3^--N were observed in the bottom two depth increments of 15-30 and 30-60 cm. This could be a result of nitrate leaching. Levels of NO_3^--N were significantly higher in the 37,000 L ha^{-1} treatment compared to the 37,000 L ha^{-1} + nitrification inhibitor, which was also higher than the 0 L ha^{-1} treatment at the 15-30 cm depth. The 37,000 L ha^{-1} and 37,000 L ha^{-1} + nitrification inhibitor treatments were higher than the 0 L ha^{-1} treatment in the 30-60 cm depth. Higher levels of NO_3^--N at the 15-30 cm depth could be a result of more of the NH_4^+-N in the LSM being converted to NO_3^- in the 37,000 L ha^{-1} without the nitrification inhibitor. This additive NO_3^--N appears to have been leached below the 15 cm depth and accumulated in the 15-30 cm depth.

Biweekly soil samples taken throughout the six two-week sampling periods of 2006 did not show any differences in the amounts of NH_4^+-N and NO_3^--N (Table 4.8) between the manure treatments with or without the nitrification inhibitor.

Table 4.7 Pre-seeding soil NH_4^+-N and NO_3^--N levels at Dixon, SK in 2006.

	NH_4^+-N			NO_3^--N		
Treatment	**0-15**	**15-30**	**30-60**	**0-15**	**15-30**	**30-60**
	kg N ha^{-1}					
0 L ha^{-1} yr^{-1}	5.48	6.73	10.35	12.35	5.43	7.65
37,000 L ha^{-1} yr^{-1}	5.28	5.33	8.45	38.10	36.35	19.83
37,000 L ha^{-1} yr^{-1}†	8.68	5.80	7.88	38.65	18.05	19.13
$LSD_{(0.10)}$	2.32	NS‡	NS	NS	9.40	7.70

† denotes addition of a nitrification inhibitor at 0.275 mL kg^{-1}.
‡ Not significant at $\alpha = 0.10$.

Table 4.8 Amounts of NH_4^+-N and NO_3^--N in 0-15 cm soil samples taken throughout the 2006 growing season at Dixon, SK.

	Sampling dates					
Treatment	**May 31**	**June 14**	**June 28**	**July 12**	**July 26**	**August 9**
	kg N ha^{-1}					
NH_4^+-N						
0 L ha^{-1} yr^{-1}	7.5	18.7	24.5	16.0	14.8	11.7
37,000 L ha^{-1} yr^{-1}	6.2	20.1	24.5	16.4	14.6	12.1
37,000 L ha^{-1} yr^{-1}†	5.4	22.9	21.3	16.4	15.0	9.9
$LSD_{(0.10)}$	1.1	NS‡	NS	NS	NS	NS
NO_3^--N	kg N ha^{-1}					
0 L ha^{-1} yr^{-1}	13.65	16.90	14.25	13.00	7.85	8.10
37,000 L ha^{-1} yr^{-1}	25.00	21.15	12.55	12.65	9.10	8.50
37,000 L ha^{-1} yr^{-1}†	20.65	17.30	14.20	14.80	8.80	7.55
$LSD_{(0.10)}$	NS‡	NS	NS	NS	NS	NS

† denotes addition of a nitrification inhibitor at 0.275 mL kg^{-1}.
‡ Not significant at $\alpha = 0.10$.

There were no differences in supply rates of NH_4^+-N observed among treatments during the 2006 growing season (Table 4.9). Supply rates of NO_3^--N did not show any differences until the July 26, and August 9 sampling dates. During these two sampling periods the supply rates of NH_4^+-N and NO_3^--N in the 37,000 L ha^{-1} and 37,000 L ha^{-1} + nitrification inhibitor treatments were higher than the 0 L ha^{-1} treatment, but were not significantly different from each other (Table 4.9).

Table 4.9 Ammonium-N and nitrate-N supply rates (μg N cm^{-2}) measured in-field at Dixon, SK in 2006 for control, and injected liquid swine manure without and with an added nitrification inhibitor.

	Sampling dates					
Treatment	**May 31**	**June 14**	**June 28**	**July 12**	**July 26**	**August 9**
	----------μg N cm^{-2}----------					
NH_4^+-N						
0 L ha^{-1} yr^{-1}	0.15	0.09	0.15	0.17	1.15	1.27
37,000 L ha^{-1} yr^{-1}	0.13	0.10	0.14	0.17	1.51	1.52
37,000 L ha^{-1} yr^{-1}†	0.11	0.09	0.13	0.15	1.45	1.26
$LSD_{(0.10)}$	NS‡	NS	NS	NS	NS	NS
NO_3^--N	----------μg N cm^{-2}----------					
0 L ha^{-1} yr^{-1}	18.7	9.6	9.0	11.4	6.6	6.4
37,000 L ha^{-1} yr^{-1}	18.6	12.0	10.5	13.7	14.0	13.6
37,000 L ha^{-1} yr^{-1}†	18.8	8.2	8.8	12.6	10.6	13.9
$LSD_{(0.10)}$	NS‡	NS	NS	NS	3.5	4.7

† denotes addition of a nitrification inhibitor at 0.275 mL kg^{-1}.
‡ Not significant at $\alpha = 0.10$.

4.1.4 2006 plant total N

During the first sampling period on June 14, there were no differences in flax biomass produced among treatments (Figure 4.3). For the remaining sampling periods, the 37,000 L ha^{-1} and 37,000 L ha^{-1} + nitrification inhibitor had significantly higher biomass than the 0 L ha^{-1} treatment. Although not significant at $\alpha \leq 0.10$, there was a trend towards slightly higher plant biomass production in the 37,000 L ha^{-1} + nitrification inhibitor treatment compared to the 37,000 L ha^{-1} treatment.

Uptake of N by the flax throughout the 2006 growing season followed a similar trend as plant biomass production. No differences were observed for the first and last sampling dates of June 14 and August 9, respectively. During all other sampling dates the 37,000 L ha^{-1} and 37,000 L ha^{-1} + nitrification inhibitor treatments were not different from one another, but were both higher than the 0 L ha^{-1} treatment (Table 4.10). Although not different at $\alpha \leq 0.10$, a similar trend toward greater flax uptake by the 37,000 L ha^{-1} + nitrification inhibitor compared to the 37,000 L ha^{-1} treatment was observed.

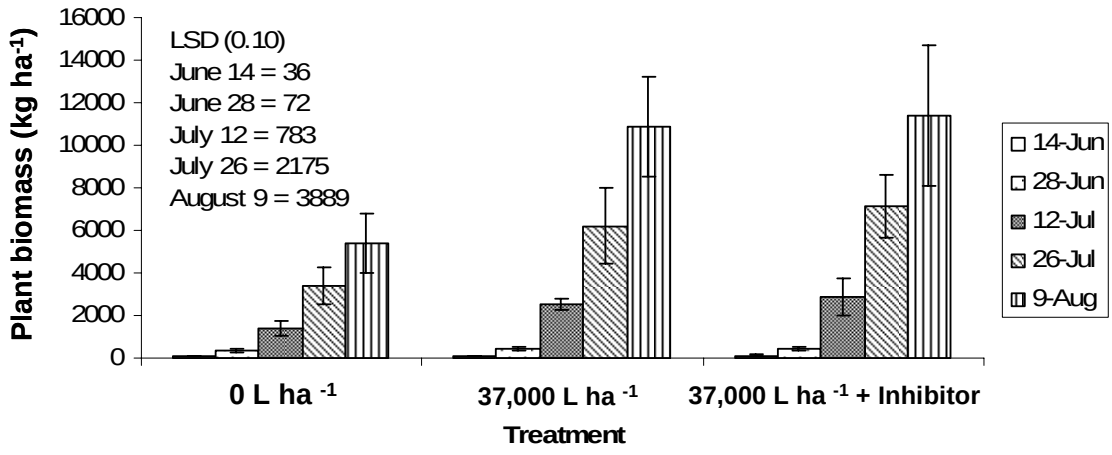

Figure 4.3 Early season flax biomass (kg ha^{-1}) measured over two week intervals in the 2006 growing season at Dixon, SK.

Table 4.10 Nitrogen uptake (kg N ha^{-1}) by flax in the 2006 growing season at Dixon, SK.

	Sampling dates				
Treatment	**June 14**	**June 28**	**July 12**	**July 26**	**August 9**
	---------- kg N ha^{-1} ----------				
0 L ha^{-1} yr^{-1}	0.24	0.91	2.99	5.61	7.25
37,000 L ha^{-1} yr^{-1}	0.29	1.34	7.84	11.91	17.29
37,000 L ha^{-1} yr^{-1}†	0.33	1.27	8.62	14.41	18.07
$LSD_{(0.10)}$	NS‡	0.23	2.19	4.58	NS

† denotes addition of a nitrification inhibitor at 0.275 mL kg^{-1}.
‡ Not significant at $\alpha = 0.10$.

At maturity, the harvest samples of flax showed significantly higher N uptake and seed yield in the 37,000 L ha^{-1} and 37,000 L ha^{-1} + nitrification inhibitor treatments compared to the 0 L ha^{-1}, but were not different from each other (Table 4.11). No differences were observed for % N recovery between the 37,000 L ha^{-1} and 37,000 L ha^{-1} + nitrification inhibitor treatments.

No differences in residual soil NH_4^+-N and NO_3^--N were observed to a depth of 60 cm in the fall of 2006 for 0 L ha^{-1}, 37,000 L ha^{-1}, and 37,000 L ha^{-1} + nitrification inhibitor treatments (Appendix G).

Table 4.11 Harvest N uptake, seed yield, and percent recovery of applied N in flax in 2006 at Dixon, SK.

	Treatment			
	0 L ha^{-1} yr^{-1}	**37,000 L ha^{-1} yr^{-1}**	**37,000 L ha^{-1} yr^{-1}†**	**LSD$_{(0.10)}$**
N uptake ‡	3.6 (b)	16.8 (a)	13.2 (a)	5.2
Seed yield ‡	996 (b)	2839 (a)	2737 (a)	863
% N recovery	NA	78.9 (a)	73.9 (a)	9.5

† denotes addition of a nitrification inhibitor at 0.275 mL kg^{-1}.
‡ N uptake and seed yield are reported as kg ha^{-1}.
Values in a row following same letter are not significantly different ($\alpha = 0.10$).

The less apparent effect of the nitrification inhibitor treatment in the 2006 field season with flax compared to 2005 with wheat could be a result of different environmental conditions, duration of product efficacy, and cropping choices. The 2006 field season experienced well above normal precipitation in the latter part of May and the beginning of June (Table 3.6) which was likely responsible for the leaching of NO_3^--N out of the soil surface, while the soil sampling and PRS probes were limited to observations of N in the 0-15 cm depth. The LSM for the 2006 growing season was applied in the fall of 2005. It is important to recognize that the nitrification inhibitor would have been effective in keeping the LSM-N in the NH_4^+ form in the late fall and early spring, but the inhibition effects likely diminished by the time seeding and field sampling began at the end of May in the 2006 growing season. If the inhibitory effect of the nitrification inhibitor had diminished by the time of potential high loss in late May and June when very wet conditions were experienced, equally high losses in treatments with and without a nitrification inhibitor would be expected. The low responsiveness of flax to N fertilizer (Thavarajah, 2002) would also contribute to lack of crop treatment effects observed in 2006 compared to the 2005 season.

4.2 Effects of Supplemental Commercial Fertilizer on Yield and N Recovery

4.2.1 Supplemental phosphorus at Dixon

4.2.1.1 2004

The effects of supplemental commercial P fertilizer on seed yield and crop N recovery of the N applied in the LSM were investigated in three field seasons with different crops and manure application times. Early frost in the fall of 2004 damaged the canola crop and therefore only biomass yields could be obtained (Table 4.12). There were no differences in biomass production between LSM treatments without and with supplemental P fertilizer. However, an increase in biomass resulted from the supplemental P fertilizer in the 100 kg N ha^{-1} of urea fertilizer treatment. Absence of a significant increase in biomass production from P fertilizer addition in LSM treatments may be a result of the addition of P in the LSM itself. Leibig's Law of the Minimum states that the most limiting factor determines yield potential (Havlin et al., 2005). Response to supplemental P fertilizer in the urea treatment indicates a P deficiency. The application of N fertilizer only for 8 years resulted in a negative P balance and draw down of soil P supply at this site as reported by Stumborg (2006).

Content of N in the plant surface biomass followed similar trends as biomass yield. No differences were observed in biomass N content with added P fertilizer in the LSM treatments, with the exception of the urea fertilizer treatment which had significantly higher N concentration with the supplemental P fertilizer (Appendix B). Phosphorus supplied in the LSM was sufficient to alleviate any deficiencies that may have occurred in the LSM treatments.

Crop recovery of N applied in LSM and urea fertilizer did not differ with the addition of supplemental P fertilizer (Table 4.13). Although not significant, there was a general trend towards greater crop N recovery in the LSM and urea when P fertilizer was added.

Table 4.12 Canola biomass production at Dixon, SK in 2004, without and with sub-treatments of phosphorus fertilizer.

Treatment	Phosphorus sub-treatment		LSD (0.10)
	0 kg P ha^{-1}	6.5 kg P ha^{-1}	
	----------kg ha^{-1}----------		
0 L ha^{-1} Injector pass	540	780	NS
37,000 L ha^{-1} applied annually	4948	5638	NS
74,000 L ha^{-1} applied annually	5883	6180	NS
148,000 L ha^{-1} applied annually	6238	5915	NS
100 kg N ha^{-1} applied annually †	3278	4798	1110

† denotes fertilizer N applied as urea (46-0-0).

Table 4.13 Percent recovery of added N in canola biomass at Dixon, SK in 2004, without and with sub-treatments of phosphorus fertilizer.

Treatment	Phosphorus sub-treatment		LSD (0.10)
	0 kg P ha^{-1}	6.5 kg P ha^{-1}	
	----------% N recovery----------		
37,000 L ha^{-1} applied annually	73.6	104.4	NS
74,000 L ha^{-1} applied annually	60.7	63.3	NS
148,000 L ha^{-1} applied annually	27.2	23.1	NS
100 kg N ha^{-1} applied annually †	20.7	41.0	NS

† denotes fertilizer N applied as urea (46-0-0).

Fall soil samples (0-30 cm) were taken to determine if any differences existed in fall soil N concentrations. There were no significant differences in fall soil NH_4^+-N in the 0 L ha^{-1} and 37,000 L ha^{-1} LSM and 100 kg N ha^{-1} urea treatments with and without P fertilizer (Appendix C). The P fertilizer addition lowered fall soil NH_4^+-N in the 74,000 L ha^{-1} and 148,000 L ha^{-1} LSM treatments. No significant differences in fall NO_3^--N were observed between the treatments evaluated.

4.2.1.2 2005

In 2005 increases in seed yield of wheat were observed with the addition of supplemental P fertilizer in the 37,000 L ha^{-1} LSM treatment, and the 100 kg N ha^{-1} urea treatment (Table 4.14). A large positive response to added P fertilizer suggests that P was limiting wheat yield in these treatments. However, seed yield was lowered with the supplemental P fertilizer in the 148,000 L ha^{-1} LSM treatment. Sufficient P was likely supplied in the LSM, and the additional P applied through

the supplemental P fertilizer may have resulted in a detrimental salt or toxicity effect on the wheat.

Grain N concentrations were not greatly affected in the 0 L ha^{-1} LSM and 100 kg N ha^{-1} urea treatments, but were higher in the 37,000 L ha^{-1}, 74,000 L ha^{-1} and 148,000 L ha^{-1} LSM treatments with P fertilizer amendment (Appendix D).

Table 4.14 Wheat seed yield at Dixon, SK in 2005, without and with sub-treatments of phosphorus fertilizer.

Treatment	Phosphorus sub-treatment		LSD (0.10)
	0 kg P ha^{-1}	6.5 kg P_2O_5 ha^{-1}	
	----------kg ha^{-1}----------		
0 L ha^{-1} Injector pass	1095	1226	NS
37,000 L ha^{-1} applied annually	3359	3982	580
74,000 L ha^{-1} applied annually	3755	3626	NS
148,000 L ha^{-1} applied annually	4062	3405	580
100 kg N ha^{-1} applied annually †	2705	3710	580

† denotes fertilizer N applied as urea (46-0-0).

No differences were observed in % N recovery in the wheat in 2005 (Table 4.15) as related to P fertilization. However, as in 2004, there was slightly higher crop N recovery in the 37,000 L ha^{-1} LSM and 100 kg N ha^{-1} urea treatment. This suggests that there may have been a P deficiency that was alleviated through the supplemental P fertilizer, resulting in a higher proportion of the N applied recovered in the crop. The crop N recovery was not affected in the 74,000 L ha^{-1} LSM treatment which suggests that at this rate, sufficient P was supplied in the LSM to maximize seed yield.

Table 4.15 Percent recovery of added N by wheat at Dixon, SK in 2005, without and with sub-treatments of phosphorus fertilizer.

Treatment	Phosphorus sub-treatment		LSD (0.10)
	0 kg P ha^{-1}	6.5 kg P ha^{-1}	
	----------% N recovery----------		
37,000 L ha^{-1} applied annually	66.8	83.3	NS
74,000 L ha^{-1} applied annually	51.6	51.7	NS
148,000 L ha^{-1} applied annually	33.4	26.8	NS
100 kg N ha^{-1} applied annually †	51.4	64.7	NS

† denotes fertilizer N applied as urea (46-0-0).

Fall soil samples were taken at the 0-30 and 30-60 cm depth increments in treatments without and with supplemental P fertilizer. No differences in soil NH_4^+-N or NO_3^--N concentrations were observed in either depth increment for LSM treatments without and with supplemental P fertilizer (Appendix E).

4.2.1.3 2006

No significant differences in flax seed yield were observed for the 2006 field season without and with supplemental P fertilizer (Table 4.16). Although not statistically significant there was a trend towards lower seed yield with the addition of P fertilizer. Flax was seeded in a broadcast and incorporation method, with shallow incorporation. This seeding method may have resulted in inadequate separation between the flax seeds and the supplemental P fertilizer, which could have caused seeding injury and ultimately lower seed yield and N recovery.

Grain N contents were not significantly affected by P fertilization in any of the LSM treatments (Appendix F). Grain N content was elevated with the supplemental P fertilizer in the urea treatment.

Table 4.16 Flax seed yield at Dixon, SK in 2006, without and with sub-treatments of phosphorus fertilizer.

Treatment	Phosphorus sub-treatment		LSD $_{(0.10)}$
	0 kg P ha^{-1}	6.5 kg P ha^{-1}	
	----------kg ha^{-1}----------		
0 L ha^{-1} Injector pass	996	970	NS
37,000 L ha^{-1} applied annually	2839	2364	NS
74,000 L ha^{-1} applied annually	3079	2504	NS
148,000 L ha^{-1} applied annually	2963	2383	NS
100 kg N ha^{-1} applied annually †	2463	2172	NS

† denotes fertilizer N applied as urea (46-0-0).

Similar to seed yield, there was a trend towards lower N recovery by the flax in the LSM and urea treatments with the supplemental P fertilizer (Table 4.17). Crop N recovery was lowered by the addition of P fertilizer in the 37,000 L ha^{-1} and 74,000 L ha^{-1} LSM treatments. The decrease in crop N recovery was larger in the LSM treatments compared to the urea only treatment when P fertilizer was added.

Additional salt in the vicinity of the root zone with manure may have created some additional potential for injury.

Table 4.17 Percent recovery of added N by flax at Dixon, SK in 2006, without and with sub-treatments of phosphorus fertilizer.

Treatment	Phosphorus sub-treatment		LSD $_{(0.10)}$
	0 kg P ha^{-1}	6.5 kg P ha^{-1}	
	----------% N recovery----------		
37,000 L ha^{-1} applied annually	78.9	62.0	8.5
74,000 L ha^{-1} applied annually	47.0	34.7	8.5
148,000 L ha^{-1} applied annually	24.7	17.3	NS
100 kg N ha^{-1} applied annually †	45.1	40.6	NS

† denotes fertilizer N applied as urea (46-0-0).

Fall soil concentrations of NH_4^+-N in the 0-30 cm depth (Appendix G) were not greatly affected by P fertilization, with the exception of the 148,000 L ha^{-1} and 100 kg N ha^{-1} urea treatments, where soil in the sub-treatment of P fertilizer had higher NH_4^+-N concentrations. This would be expected if P fertilizer was reducing yield and N uptake. No differences in NO_3^--N concentrations were observed in the 0-30 cm depth with the exception of the 148,000 L ha^{-1} treatment, where the soil that did not receive the supplemental P fertilizer had higher NO_3^--N concentrations (Appendix G). There were no differences in the NH_4^--N concentrations in the 30-60 cm depth. Supplemental P fertilization did not result in any large differences at any depth, with the exception of the 148,000 L ha^{-1} LSM treatment at the 30-60 cm depth. Higher NO_3^--N concentrations (368 kg NO_3^--N ha^{-1}) were observed in the 148,000 L ha^{-1} LSM treatment without P fertilizer at the 30-60 cm depth. There may have been greater movement of NO_3^--N below the rooting zone in the 148,000 L ha^{-1} LSM treatment without P fertilizer addition.

Overall, lack of any consistent positive response of yield (only positive response was with wheat at of 37,000 L ha^{-1} rate in 2005) and N recovery (no positive response in any of the three years) to the addition of supplemental P fertilizer in the LSM treatments indicates that this practice would not be beneficial. The exception is urea fertilized soil in which soil P reserves have been depleted and

P responsive crops like canola and wheat are grown. Otherwise it appears that sufficient P is added and made available in the LSM.

4.2.2 Supplemental sulfur at Melfort

4.2.2.1 2004

Sulfur sub-treatments of elemental S and potassium sulfate were applied at 40 kg S ha^{-1} to the east end of the LSM treatments every three years starting in 2002, and repeated in 2005. Therefore, some supplemental S that would have been available to the oat crop in 2004, may have been supplied through residual S from the application in 2002. Oat seed yield was not greatly affected by S fertilization in four of the five fertilizer treatments (Table 4.18). Seed yield was higher in the 111,000 L ha^{-1} LSM applied every three years (last applied in the fall of 2002) treatment with no supplemental S fertilizer, compared to both sub-treatments of S fertilizer.

Table 4.18 Oat seed yield at Melfort, SK in 2004, without and with sub-treatments of sulfur fertilizer.

	Sulfur sub-treatment			
	No S Fertilizer	**40 kg S° ha^{-1} †**	**40 kg S ha^{-1} ††**	**LSD $_{(0.10)}$**
	----------kg ha^{-1}----------			
0 L ha^{-1}	2375	2430	2904	NS
37,000 L ha^{-1}	5039	5055	4656	NS
74,000 L ha^{-1}	4641	5211	4736	NS
111,000 L ha^{-1}	4997	4566	4139	769
80 kg N ha^{-1} Urea	4720	5048	4497	NS

† denotes application of elemental sulfur (Tiger 90).
†† denotes application of potassium sulfate.

Crop N recovery was different between the 37,000 L ha^{-1} LSM and the 80 kg N ha^{-1} urea treatments with and without S fertilizer (Table 4.19). Crop N recovery was higher in the 37,000 L ha^{-1} LSM with no S fertilizer than both sub-treatments of S fertilizer, which were not different from one another. In the 80 kg N ha^{-1} urea treatment with no S fertilizer, N recovery was higher than in the sub-treatment of potassium sulfate but not from the elemental S sub-treatment. Crop N recovery tends to decrease from the treatments without supplemental fertilizer to the sub-

treatments of S fertilizer. This may be the result of the fertilizer application date, previous crops grown and their nutrient utilization. Supplemental S fertilizer was last applied in the spring of 2002, therefore the crops grown prior to 2004 would have had access to the S fertilizer. Canola was grown in 2003, which could have used up much of the S supplied through the supplemental fertilizers as well as more of other nutrients like N which may now become more limiting. The potassium sulfate would become plant available much sooner compared to the elemental S that must be oxidized to sulfate first. Slow oxidation can result in more S available for plant uptake in subsequent years (Wen et al., 2003b). Although not significant in all treatments, there tends to be higher percent N recovery in the elemental S sub-treatment compared to the potassium sulfate sub-treatment. Elemental S sub-treatments may maintain S supplies in later years, closer to the crop's requirements for maximizing yield and N recovery. The higher N recoveries in 2004 in oats without S, versus with S added in 2002 may be due to lack of utilization of N in the minus S treatment, especially in canola in 2003, which carried over and supplied more N in 2004, giving rise to greater apparent recovery. Calculated percent N recovery values > 100% for the 2004 season seem to support this.

Table 4.19 Percent recovery of added N in oat crop at Melfort, SK in 2004, without and with sub-treatments of sulfur fertilizer.

	Sulfur sub-treatment			
	No S Fertilizer	**40 kg S° ha^{-1} †**	**40 kg S ha^{-1} ††**	**LSD $_{(0.10)}$**
	----------%N recovery----------			
37,000 L ha^{-1}	144.4	112.6	99.2	16.6
74,000 L ha^{-1}	77.8	69.5	68.2	NS
111,000 L ha^{-1}	29.6	19.5	13.6	NS
80 kg N ha^{-1} Urea	101.7	94.8	83.3	16.6

† denotes application of elemental sulfur (Tiger 90).
†† denotes application of potassium sulfate.

Grain N contents were different in all treatments with the exception of the 37,000 L ha^{-1} LSM treatment (Appendix I). In the 37,000 L ha^{-1} treatment, grain N was higher without S fertilizers and the 37,000 L ha^{-1} with K_2SO_4 had higher grain N compared to the same treatment with elemental S. Grain N contents were highest

without the supplemental S fertilizer in the LSM treatments. Grain N was increased in the 80 kg N ha^{-1} urea treatment with the addition of supplemental S fertilizers.

Fall soil samples were collected from the regular treatments that did not receive supplemental S fertilizer and the sub-treatments of potassium sulfate only (Appendix J). Samples were taken in the 0-30, 30-60 and 60-90 cm depth increments. Higher levels of NH_4^+-N were observed for nearly all the depths for the sub-treatments of potassium sulfate. Higher levels of soil NH_4^+-N and lower seed yield in the K_2SO_4 sub-treatments are likely due to the high amount of K that was added through the K_2SO_4. Large amounts of K would compete for exchange sites on soil colloids and displace NH_4^+ making it vulnerable to movement within the profile. Movement below the crops rooting zone would explain the lower seed yield and higher soil NH_4^+-N deeper in the profile. No significant differences in NO_3^--N were observed at any depth for any treatment.

4.2.2.2 2005

Supplemental elemental S and potassium sulfate fertilizer treatments were re-applied in the spring of 2005 in the same strips as 2002 at a rate of 40 kg S ha^{-1}. No differences in seed yield were observed in the LSM treatments of canola (Table 4.20) as influenced by S fertilization. A large difference in seed yield was observed in the 80 kg N ha^{-1} urea treatment. Both, urea plus elemental S and urea plus potassium sulfate treatments produced higher seed yield than the urea treatment alone, but were not different from each other. The urea alone treatment, without S fertilizer, greatly inhibited canola seed set, as the recorded mean seed yield was 1 kg ha^{-1}. The high S demand of the canola crop combined with little or no S supplied by soil or fertilizer, resulted in a severe N induced sulfur deficiency and toxicity (Malhi et al., 2005). No significant differences in seed yield measured in the year of application between LSM treatments that did and did not receive supplemental S fertilizer is in contrast to earlier work reported by Schoenau and Davis (2006). Schoenau and Davis (2006) reported significant increases in oat yield in 2002 at the same experimental site when 40 kg ha^{-1} of supplemental S fertilizer was added to the 37,000 L ha^{-1} and the 80 kg N ha^{-1} urea treatments.

Table 4.20 Canola seed yield at Melfort, SK in 2005, without and with sub-treatments of sulfur fertilizer.

	Sulfur sub-treatment			
	No S Fertilizer	**40 kg S° ha^{-1} †**	**40 kg S ha^{-1} ††**	**LSD $_{(0.10)}$**
	----------kg ha^{-1}----------			
0 L ha^{-1}	430	309	387	NS
37,000 L ha^{-1}	1544	1436	1576	NS
74,000 L ha^{-1}	1153	1120	1171	NS
111,000 L ha^{-1}	826	635	593	NS
80 kg N ha^{-1} Urea	1	1322	1301	386

† denotes application of elemental sulfur (Tiger 90).
†† denotes application of potassium sulfate.

Crop N recovery was not different in the LSM treatments without and with supplemental S fertilizer (Table 4.21). The crop N recovery in the 80 kg N ha^{-1} urea treatment was higher with both of the supplemental S fertilizers. Although not significant, it is interesting to note that the seed yield and % N recovery were similar and slightly higher in the elemental S fertilizer sub-treatments. Seed yield and % N recovery could be higher in the elemental S treatment due to higher S availability. Conditions of the 2005 field season may have been adequate to oxidize sufficient amounts of elemental S, from the application in 2005 and 2002 to maximize yield.

Table 4.21 Percent recovery of added N in canola at Melfort, SK in 2005, without and with sub-treatments of sulfur fertilizer.

	Sulfur sub-treatment			
	No S Fertilizer	**40 kg S° ha^{-1} †**	**40 kg S ha^{-1} ††**	**LSD $_{(0.10)}$**
	----------% N recovery----------			
37,000 L ha^{-1}	52.9	47.2	58.6	NS
74,000 L ha^{-1}	19.9	20.4	18.4	NS
111,000 L ha^{-1}	4.3	3.4	2.0	NS
80 kg N ha^{-1} Urea	17.4	53.2	43.8	22.0

† denotes application of elemental sulfur (Tiger 90).
†† denotes application of potassium sulfate.

Grain N content was not different in the LSM treatments with or without S fertilizer added but was increased by the addition of both S fertilizers in the urea fertilizer treatment (Appendix K). Sulfur deficiency in the urea only treatment resulted in low seed yield (1 kg ha^{-1}), due to an unfavorable N:S ratio. When

supplemental S fertilizers were added higher plant available S allowed for greater seed yield and increased grain N content.

Significant differences in soil NH_4^+-N were observed in all treatments at the 0-30 cm depth increment with the exception of the 0 L ha^{-1} treatment (Appendix L). In all treatments with significant differences, the sub-treatments with S fertilizers had lower NH_4^+-N concentrations than without S fertilizer. This may reflect higher N removal by the crop in the S sub-treatments. No differences in NO_3^--N were observed in any of the treatments without or with supplemental S fertilizer at the 0-30 cm depth (Appendix L). The amount of NH_4^+-N and NO_3^--N were not different at the 30-60cm depth with the exception of NO_3^--N in the 74,000 L ha^{-1} (applied every 2 years) treatment. In the 74,000 L ha^{-1} (applied every 2 years) treatment, the sub-treatment of potassium sulfate had higher NO_3^--N than without S fertilizer, but not different than the elemental S fertilizer sub-treatment.

4.2.2.3 2006

In 2006, the second year following re-application of the S fertilizer treatments, the seed yield of barley was affected by S fertilizer sub-treatments in the 37,000 L ha^{-1} LSM and 80 kg N ha^{-1} urea treatments (Table 4.22). Seed yield was not affected by S fertilizers in all other treatments. In the 37,000 L ha^{-1} LSM treatment without S fertilizer, seed yield was higher than in the LSM treatment with potassium sulfate, but was not different from the treatment with elemental S sub-treatment. Higher seed yield in the 37,000 L ha^{-1} with no S fertilizer compared to with elemental S or potassium sulfate fertilizer, could be a result of higher amounts of NH_4^+-N observed in the 0-30 cm depth in the fall of 2005. Addition of elemental S fertilizer in the 80 kg ha^{-1} urea treatment resulted in significantly higher barley seed yield than without any S fertilizer, but not significantly different than potassium sulfate. Sulfur supplied through the LSM in the 37,000 L ha^{-1} treatment appears to have sufficient amounts of S to alleviate any S deficiency issues. Increases in seed yield with the addition of S fertilizers in the 80 kg N ha^{-1} urea treatment is similar to results reported by Schoenau and Davis (2006), where oat responded strongly to supplemental S fertilizer.

Table 4.22 Barley seed yield at Melfort, SK in 2006, without and with sub-treatments of sulfur fertilizer.

	Sulfur sub-treatment			
	No S Fertilizer	**40 kg S ha^{-1} †**	**40 kg S ha^{-1} ††**	**LSD $_{(0.10)}$**
	----------kg ha^{-1}----------			
0 L ha^{-1}	1472	1527	1716	NS
37,000 L ha^{-1}	4959	4424	4033	765
74,000 L ha^{-1}	4628	4951	4839	NS
111,000 L ha^{-1}	5253	5647	5094	NS
80 kg N ha^{-1} Urea	2261	4883	4244	765

† denotes application of elemental sulfur (Tiger 90).
†† denotes application of Potassium sulfate.

Crop N recovery was not affected by S fertilizer treatment in the 74,000 L ha^{-1} and 148,000 L ha^{-1} LSM treatments, but was different in the 37,000 L ha^{-1} LSM and 80 kg N ha^{-1} urea treatments (Table 4.23). In the 37,000 L ha^{-1} LSM treatment, crop N recovery was higher without any supplemental S fertilizer compared to the two sub-treatments of S fertilizer, which were not different from one another. In the 80 kg N ha^{-1} urea treatment, the sub-treatment of elemental S fertilizer had a higher %N recovery than the sub-treatment of potassium sulfate, but not different than the treatment without any supplemental S fertilizer. Lower %N recovery in the K_2SO_4 sub-treatment may be due to lower N availability, as a result of NH_4^+ displacement and leaching by large amounts of K supplied in the K_2SO_4.

Table 4.23 Percent recovery of added N in barley at Melfort, SK in 2006, without and with sub-treatments of sulfur fertilizer.

	Sulfur sub-treatment			
	No S Fertilizer	**40 kg S ha^{-1} †**	**40 kg S ha^{-1} ††**	**LSD $_{(0.10)}$**
	----------kg ha^{-1}----------			
37,000 L ha^{-1}	77.5	57.1	50.6	16.7
74,000 L ha^{-1}	46.7	42.9	38.5	NS
111,000 L ha^{-1}	31.0	31.1	23.1	NS
80 kg N ha^{-1} Urea	65.3	80.1	52.3	16.7

† denotes application of elemental sulfur (Tiger 90).
†† denotes application of potassium sulfate.

Grain N contents were not affected by treatment in the 0 L ha^{-1} and 111,000 L ha^{-1} LSM treatments (Appendix M). Large differences in grain N were observed

in the 37,000 L ha^{-1} LSM, 74,000 L ha^{-1} LSM and 80 kg N ha^{-1} urea treatments. In the 37,000 L ha^{-1} LSM treatment grain N content was higher in the potassium sulfate sub-treatment compared to the elemental S sub-treatment but not different from the treatment without supplemental S fertilizer. In the 74,000 L ha^{-1} LSM treatment higher grain N was observed without any supplemental S fertilizer compared to the sub-treatment of elemental S fertilizer but was not different from the sub-treatment of potassium sulfate. The two sub-treatments of S fertilizer were not different from one another in the 74,000 L ha^{-1} LSM treatment. Grain N in the 80 kg N ha^{-1} urea treatment was higher with no supplemental S compared to both sub treatments of S fertilizers.

No differences were observed in fall soil samples for NH_4^+-N and NO_3^--N content in the 0-30 and 30-60 cm depths (Appendix N).

Overall, added S fertilizer had the largest effects on yield and N recovery when a high S demanding crop like canola was grown on the urea only fertilized treatment. Elemental S and sulfate forms were both effective. It appears that sufficient available S was added in the manure itself (~ 7 kg S ha^{-1}) in the 37,000 L ha^{-1} LSM treatment), to supply S for the crops and conditions at Melfort in 2004, 2005 and 2006.

5 GENERAL DISCUSSION

The addition of a nitrification inhibitor to LSM applied at an agronomic rate of 37,000 L ha^{-1} (~ 100 kg N ha^{-1}) is capable of maintaining higher concentrations and supply rates of NH_4^+-N in the soil compared to 37,000 L ha^{-1} of LSM without a nitrification inhibitor. Inhibition of the nitrification process was more evident in the 2005 field season (spring application) compared to the 2006 field season (previous fall application). In 2005 higher levels of N remained in the NH_4^+ form early in the growing season with the addition of the nitrification inhibitor to LSM compared to the LSM treatment that did not receive the inhibitor. Evidence of N remaining in the NH_4^+ form longer was observed through higher NH_4^+ concentrations in soil samples and higher PRS NH_4^+-N supply rates early on in the growing season. However, the net effect of the nitrification inhibitor on final crop yield and recovery of manure N in the crop was minimal in the 2005 growing season.

In 2006 there was a reduced response to the nitrification inhibitor compared to 2005. No large differences were observed in yield and plant N, soil N or PRS NH_4^+-N and NO_3^--N supply rates throughout the growing season between the LSM treatment that received the nitrification inhibitor and the LSM treatment that did not. A decreased response to the nitrification inhibitor in the 2006 field season could be the combined result of environmental conditions, product efficacy and cropping choices. Above average precipitation received during the end of May and the first part of June in 2006 was likely responsible for the leaching of NO_3^--N to depths greater than the 0-15 cm depth that the biweekly soil samples and PRS^{TM} probes were able to access. The LSM for the 2006 growing season was applied in the fall of 2005, compared to the 2005 field season where LSM was applied in the spring just prior to seeding operations and field measurements. The nitrification inhibitor appears to have been effective in keeping LSM-N in the NH_4^+ form up to early spring of 2006, but the inhibition effects appear to have diminished by the time

seeding and field sampling began at the end of May. As well, the general low responsiveness of flax to N fertilizer contributed to the lack of crop treatment effects observed in the 2006 field season compared the 2005 season. It appears that the use of a nitrification inhibitor can be effective in maintaining LSM-N in the NH_4^+ form longer and potentially reduce losses. However, lack of observed differences in final N recovery and seed yield with the addition of the nitrification inhibitor in this study may be a reflection of a relatively low N loss potential at these study site years on the prairies compared to other regions where significant effects have been observed.

The addition of supplemental P fertilizer did not result in any increases in canola biomass production or plant N contents in LSM treatments in 2004. Biomass production and plant N contents were increased with supplemental P fertilizer in the 100 kg N ha^{-1} urea treatment, indicating that the urea only treatment was the only treatment that was P deficient. In 2005 wheat seed yield was increased in the 37,000 L ha^{-1} and 100 kg N ha^{-1} urea treatments, indicating that P was limiting in these treatments. No large difference in %N recovery in the crop was observed without or with supplemental P fertilizer in any of the treatments in 2005. Flax was grown in 2006 and was not responsive to N or supplemental P fertilizer. Instead a negative response to supplemental P fertilizer occurred, as seed yield was lower in all LSM and urea treatments with P fertilizer added. Crop N recovery also decreased with supplemental P fertilizer, indicating that flax grown on swine manured soil is sensitive and not positively affected by P fertilization. Any potential response to P fertilizer for any crop would appear limited to the agronomic N rate of 37,000 L ha^{-1} and 100 kg N ha^{-1} urea fertilizer treatments, as higher rates of LSM provided enough P to maximize yield. Also the manure N:P ratio in the current study is relatively high. Using manures with lower N:P ratios than that in the current study should result in even less potential response to P fertilizer when LSM is applied at the agronomic N rate. Fertilization with urea fertilizer only (100 kg N ha^{-1} urea) for a number of years is likely to deplete P in soils as crops will remove and deplete the existing available P from the soil if no further P is added either in the form of LSM or commercial fertilizer.

Addition of supplemental S fertilizer at the Melfort field site produced variable responses related to supplemental S fertilizer and LSM application intervals, and previous crop uptake. In 2004, residual S from the supplemental elemental S and potassium sulfate fertilizer (40 kg S ha^{-1}) treatments applied in 2002 did not affect canola biomass yield in the 37,000 L ha^{-1} and 74,000 L ha^{-1} LSM treatments. Crop N recovery tended to decrease in the supplemental S treatments. This appears to be a result of the time of S fertilizer application and growing of previous crops such as canola with high N and S uptake which probably reduced carry-over of N in the S fertilized treatments. In 2005, elemental S and potassium sulfate (40 kg S ha^{-1}) were re-applied to all treatments. There were no differences between S fertilized and unfertilized canola seed yield in any of the LSM treatments. However, the 80 kg N ha^{-1} urea treatment with no S fertilizer produced virtually no seed and consequently had much decreased N recovery. Lack of seed set was likely due to a N-induced S deficiency, demonstrating the need to balance fertilizer application with crop nutrient requirements. In 2006, LSM was applied to all treatments and demonstrated that the annual low rate of 37,000 L ha^{-1} LSM was adequate to maximize seed yield. Supplemental S fertilizer in the 80 kg N ha^{-1} urea treatment resulted in an increase in barley seed yield. Overall, it appears that in 2004, 2005 and 2006 there was sufficient S in the manure treated plots such that addition of supplemental fertilizer S under these conditions would not be warranted.

6 GENERAL SUMMARY AND CONCLUSIONS

The following concluding points are made to summarize the key findings and address the objectives set out to evaluate the effects of a nitrification inhibitor, and supplemental P and S fertilizers on recovery of N added as LSM to Saskatchewan soils.

1. Use of a nitrification inhibitor can be useful in maintaining LSM-N in the NH_4^+ form longer. Benefits of the nitrification inhibitor are likely to be greatest when the inhibition coincides with the time of high potential loss of NO_3^- by leaching or denitrification.
2. Nitrogen losses at these site years on the prairies may not be large enough in most years to warrant the use of a nitrification inhibitor in LSM, and may not be economical as final effects on seed yield and N recovery were minimal.
3. The annual application of a low rate of LSM (37,000 L ha^{-1}) and 100 kg N ha^{-1} urea were most responsive to supplemental P fertilizer, indicating that the greatest need to supplement with P fertilizer is when more P is removed in crop harvest over time than is added as manure or fertilizer.
4. Application of supplemental P fertilizer did not increase seed yield or %N recovery in medium and high rates (74,000 and 148,000 L ha^{-1}) of LSM treatments, suggesting that there are sufficient amounts of P added at these rates of LSM to maximize seed yield.
5. The application of S fertilizer to soils typically deficient in available S can result in large yield response in S sensitive crops like canola when large amounts of N are added. The impact of manure addition on S availability should be assessed when considering the need for supplemental S fertilizer.

6. Low annual applications of LSM would likely be a superior but possibly less economical and practical way of supplying nutrients to the crop compared to larger semi-annual or tri-annual applications of LSM.

7 GAPS AND DIRECTIONS FOR FUTURE RESEARCH

1. Observation and evaluation of the effects of a nitrification inhibitor on crop N recovery and seed yield would be useful over many field seasons with a variety of crops in contrasting soil-climatic conditions. Emphasis should be placed on soil zones such as the Black and Grey soil zones with greater precipitation and consequently greater opportunity for N losses.
2. During the course of this study, LSM was added in the spring of one field season and the previous fall for the other field seasons. Observations made during the 2005 and 2006 field season indicate that the nitrification inhibitor was effective in maintaining LSM-N in the NH_4^+ form longer during both fall and spring application dates. However, these observations were made over only two field seasons with two different crops. Long-term evaluation of fall vs spring applied LSM with and without a nitrification inhibitor needs to be done to investigate the practicality of use of a nitrification inhibitor in LSM.
3. The work in this experiment concentrated on the crop recovery of the N applied in the LSM. It would be valuable to determine if the use of a nitrification inhibitor added to LSM can decrease N losses to the atmosphere in the form of N gasses, especially N_2O which is a powerful greenhouse gas, as N_2O is produced during both nitrification and denitrification.

8 LITERATURE CITED

Adeli, A., and J.J. Varco. 2001. Swine lagoon effluent as a source of nitrogen and phosphorus for summer forage grasses. Agron. J. 93:1174-1181.

Bakhsh, A., R.S. Kanwar, and D.L. Karlen. 2005. Effects of liquid swine manure applications of NO_3-N leaching losses to subsurface drainage water from loamy soils in Iowa. Agric. Ecosyst. Environ. 109:118-128.

Boeckx, P., X. Xu, and O. Cleemput. 2005. Mitigation of N_2O and CH_4 emission from rice and wheat cropping systems using dicyandiamide and hydroquinone. Nutr. Cycl. Agroecosyst. 72:41-49.

Chantigny, M.H., P. Rochette, and D.A. Angers. 2001. Short-term C and N dynamics in a soil ammended with pig slurry and barley straw: A field experiment. Can. J. Soil Sci. 91:131-137.

Chantigny, M.H., D.A. Angers, T. Morvan, and C. Pomar. 2004. Dynamics of pig slurry nitrogen in soil and plant as determined with ^{15}N. Soil Sci. Soc. Am. J. 68:637-643.

Coelho, B.R.B., R.C. Roy, and A.J. Bruin. 2005. Optimization of liquid swine manue sidedress rate and method for grain corn. Agron. J. 97:1322-1332.

Coelho, B.R.B., R.C. Roy, and A.J. Bruin. 2006. Nitrogen recovery and partitioning with different rates and methods of sidedressed manure. Soil Sci. Soc. Am. J. 70:464-473.

Daniel, T.C., A.N. Sharpley, D.R. Edwards, R. Wedopohl, and J.L. Lemunyon. 1994. Minimizing surface water eutrophication from agriculture by phosphorus management. J. Soil Water Conserv. 49:30-38.

Dendooven, L., E. Bonhomme, R. Merckx, and K. Vlassak. 1998b. Injection of pig slurry and its effects on dynamics of nitrogen and carbon in a loamy soil under laboratory conditions. Biol. Fertil. Soils 27:5-8.

Flowers, T.H., and J.R. O'Callaghan. 1983. Nitrification in soils incubated with pig slurry or ammonium sulphate. Soil Biol. Biochem. 15:337-342.

Gasser, J.K.R. 1970. Nitrification inhibitors - their occurance, production and effects of their use on crop yields and composition. Soils Fert. 33:547-554.

Gioacchini, P., A. Nastri, C. Marzadori, C. Gioacchini, L.V. Antisari, and C. Gessa. 2002. Influence of urease and nitrification inhibitors on N losses from soils fertilized with urea. Biol. Fertil. Soils 36:129-135.

Havlin, J.L., J.D. Beaton, S.L. Tisdale, and W.L. Nelson. 2005. Soil Fertility and Fertilizers: An intorduction to nutrient management. p. 1-515. Pearson Rentice Hall, Upper Saddle River, NJ, USA.

Hendershot, W.H., and H. Lalande. 1993. Soil Reaction and Exchangeable Acidity, p. 141-145, In M.R. Carter, ed. Soil Sampling and Methods of Analysis. Lewis Publishers, Boca Raton FL, USA.

Hoff, J.D., D.W. Nelson, and A.L. Sutton. 1981. Ammonia volatilization from liquid swine manure applied to cropland. J. Environ. Qual. 10:90-95.

Janzen, H.H. 1993. Soluble Salts, p. 161-166, *In* M.R. Carter, ed. Soil Sampling and Methods of Analysis. Lewis Publishers, Boca Raton, FL, USA.

Keeney, D.R., and D.W. Nelson. 1982. Nitrogen - inorganic forms. p.643-698. *In* A.L. Page et al. (ed) Methods of soil analysis. Part 2. Chemical and microbiological properties. Agron. Monogr. 9., ASA and SSSA, Madison, WI, USA.

Kowalenko, C.G. 1993. Extraction of Available Sulfur. p.65-74. *In* Carter, ed. Soil Sampling and Methods of Analysis. Lewis Publishers, Boca Raton, FL.

Malhi, S.S., and M. Nyborg. 1982. An evaluation of carbon disulphide as a sulphur fertilizer and as a nitrification inhibitor. Plant and Soil 65:203-218.

Malhi, S.S., and M. Nyborg. 1983. Release of mineral N from soils: influence of inhibitors of nitrification. Soil Biology & Biochemistry 15:581.

Malhi, S.S., E.D. Solberg, and M. Nyborg. 2005. Influence of formulation of elemental S fertilizer on yield, quality and S uptake of canola seed. Can. J. Plant Sci. 85:793-802.

McCormick, R.A., D.W. Nelson, A.L. Sutton, and D.M. Huber. 1983. Effect of nitrapyrin on nitrogen transformations in soil treated with liquid swine manure. Agron. J. 75:947-950.

McCormick, R.A., D.W. Nelson, A.L. Sutton, and D.M. Huber. 1984. Increased N efficiency from nityapyrin added to liquid swine manure used as a fertilizer for corn. Agron. J. 76:1010-1014.

Mooleki, S.P., J.J. Schoenau, G. Hultgreen, G. Wen, and J.L. Charles. 2002. Effect of rate, frequency and method of Liquid swine maure application of soil

nitrogen availability, crop performance and N use efficiency in east-central Saskatchewan. Can. J. Soil Sci. 82:457-467.

Morvan, T., P. Leterme, G.G. Arsene, and B. Mary. 1997. Nitrogen transformations after the spreading of pig slurry on bare soil and ryegrass using ^{15}N-labelled ammonium. Europ. J. Agronomy 7:181-188.

Qian, P., and J.J. Schoenau. 2000. Use of ion exchange membrane to assess soil N supply to canola as affected by addition of liquid swine manure and urea. Can. J. Soil Sci. 80:213-218.

Qian, P., and J.J. Schoenau. 2002. Practical applications of ion exchange resins in agricultural and environmental soil research. Can. J. Soil Sci. 82:9-21.

Qian, P., J.J. Schoenau, and R.E. Karamanos. 1994. Simultaneous extraction of available phosphorus and potassium with a new soil test - a modification of Kelowna extraction. Commun. Soil Sci. Plant Anal. 25:627-635.

Rochette, P., M.H. Chantigny, D.A. Angers, N. Bertrand, and D. Cote. 2001. Ammonia volatilization and soil nitrogen dynamics following fall application of pig slurry on canola crop residues. Can. J. Soil Sci. 81:515-523.

SAS Institute, Inc. 1985. SAS user's guide. Statistics, Version 5, ed. SAS Institute Inc, Cary, NC, USA.

Saskcatchewan Soil Survey. 1989. Rural Municipality of Humboldt No. 370. Preliminary soil map and report. Saskatchewan Institute of Pedology. University of Saskatchewan, Saskatoon, Saskatchewan, Canada

Saskatchewan Soil Survey. 1950. Soil survey of Saskatchewan: agriculturally settled areas north of township 48. Soil Survey Report No. 13. University of Saskatchewan, Saskatoon, Saskatchewan Canada.

Schoenau J.J. and B. Assefa. 2004. Land application and handling of manure.pp.97-140. *In* M. Amrani (ed), Manure research findings and technologies. AAFRD Technical Press, Edmonton, AB, Canada.

Schoenau, J.J., and J.G. Davis. 2006. Optimizing soil and plant responses to land-applied manure nutrients in the Great Plains of North America. Can. J. Soil Sci. 86:587-595.

Schoenau, J.J., K. Bolton, and K. Panchuk. 2000. Managing Manure as a Fertilizer. SUSMMF1100. Sask. Agric. and Food, Regina, Saskatchewan, Canada.

Schoenau, J.J., S.P. Mooleki, P. Qian, and S.S. Malhi. 2003. Balancing the availability of nutrients in manured soils. p. 64-68. 'Focus on the Future Conf.: Optimizing Production Systems'. Prairie Swine Center, Saskatoon, Saskatchewan, Canada.

Shoji, S., J. Delgado, A. Mosier, and Y. Miura. 2001. Use of controlled release fertilizers and nitrification inhibitors to increase nitrogen use efficiency and to conserve air and water quality. Commun. Soil Sci. Plant Anal. 32:1051.

Smith, D.R., P.A. Moore, Jr., C.V. Maxwell, B.E. Haggard, and T.C. Daniel. 2004. Reducing phosphorus runoff from swine manure with dietary phytase and aluminum chloride. J. Environ. Qual. 33:1048-1054.

Sorensen, P., and M. Amato. 2002. Remineralisation and residual effects of N after application of pig slurry to soil. Europ. J. Agronomy 16:81-95.

Stumborg, C.M. 2006. Phosphorus and nitrogen loading in manured Saskatchewan soils. M.Sc. thesis. Department of Soil Science, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.

Stumborg, C., J.J. Schoenau, and S.S. Malhi. 2007. Nitrogen balance and accumulation pattern in three contrasting prairie soils receiving repeated applications of liquid swine and solid cattle manure. Nutr. Cycl. Agroecosyst..

Sutton, A.L., D.M. Huber, D.D. Jones, and D.T. Kelly. 1990. Use of nitrification inhibitors with summer applications of swine manure. Appl. Engin. Agric. 6:296-300.

Thavarojah, D. 2001. Agronomic comparison of nitrogen fertilizer practices in Saskatchewan. M.Sc. thesis. Department of Soil Science, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.

Thomas, R.L., R.W. Sheard, and J.R. Moyer. 1967. Comparison of conventional and automated procedures for nitrogen, phosphorus, and potassium analysis of plant material using a single digestion. Agron. J. 59:240-248.

Tri-Provincial Initiative. 2003. Tri-Provincial Manure Application and Use Guidelines. Prairie Provinces' Commitee on Livestock Development and Manure Management.

Vallejo, A., L. Garcia-Torres, J.A. Diez, A. Arce, and S. Lopez-Fernandez. 2005. Comparison of N losses (NO_3^-, N_2O, NO) from surface applied, injected or ammended (DCD) pig slurry of an irrigated soil in a Mediterranean climate. Plant Soil. 272:313-325.

Wen, G., S. J.J., J.L. Charles, and S. Inanaga. 2003a. Efficiency parameters of nitrogen in hog and cattle manure in the second year following application. J. Plant Nutr. Soil Sci. 166:490-498.

Wen, G., J.J. Schoenau, S.P. Mooleki, S. Inanaga, T. Yamamoto, K. Hamamura, M. Inoue, and P. An. 2003b. Effectiveness of an elemental sulfur fertilizer in an oilseed-cereal-legume rotation on the Canadian prairies. J. Plant Nutr. Soil Sci. 166:54-60.

http://www.climate.weatheroffice.ec.gc.ca/climateData/canada_e.html

9 APPENDICES

APPENDIX A

Dixon LSM Application Dates and Nutrient Composition

Table A.1 2004, 2005, and 2006 LSM application dates and nutrient composition at Dixon, SK.

Field Season	Application Date	LSM Nutrient Composition				
		Total N	NH_4^+	Total P	Soluble inorganic P	K
		----------µg/ml----------				
2004	n/a	2547	1096	191	59	1585
2005	May 4, 2005	1498	1086	86	15	1428
2006	October 5, 2005	1050	1297	156	30	1735

APPENDIX B

Dixon Annual Grain and Straw Yields without and with P Application

Table B.1 2004 biomass yields and biomass %N at Dixon without and with 6.5 kg P ha^{-1}.

	Biomass Yield No P Fertilizer		Biomass Yield 6.5 kg P ha^{-1}	
Treatments	**Mean**	**St Dev**	**Mean**	**St Dev**
1	548	513	590	217
2	540	598	780	581
3	823	546	1168	299
4	4948	1120	5638	762
5	1863	680	2805	870
6	4613	1017	5448	767
7	5883	1004	6180	936
8	4915	683	5048	892
9	6238	436	5915	887
10	5350	1100	5133	917
11	973	744	1283	480
12	3138	934	3210	640
13	2988	1414	3983	1193
14	3278	2152	4798	1070
15	2905	1466	5115	1737
$LSD_{(0.10)}$		1110		
	Biomass %N No P Fertilizer		**Biomass %N 6.5 kg P ha^{-1}**	
	Mean	**St Dev**	**Mean**	**St Dev**
1	0.53	0.11	0.59	0.05
2	0.53	0.09	0.65	0.10
3	0.53	0.03	0.61	0.11
4	0.91	0.31	0.97	0.26
5	0.59	0.04	0.64	0.04
6	1.13	0.21	1.28	0.11
7	1.58	0.30	1.76	0.10
8	1.01	0.34	1.06	0.17
9	1.95	0.16	1.99	0.11
10	0.85	0.21	0.94	0.22
11	0.56	0.02	0.59	0.06
12	0.61	0.17	0.61	0.05
13	0.78	0.18	0.73	0.30
14	1.10	0.16	1.33	0.29
15	1.50	0.06	1.63	0.12
$LSD_{(0.10)}$		0.21		

APPENDIX C

Dixon Fall Soil NH_4^+-N and NO_3^--N without and with P Application

Table C.1 2004 fall soil NH_4^+-N and NO_3^--N at Dixon without and with 6.5 kg P ha^{-1} at 0-30 depth.

	NH_4^+-N No P Fertilizer		NH_4^+-N 6.5 kg P ha^{-1}		NO_3^--N No P Fertilizer		NO_3^--N 6.5 kg P ha^{-1}	
Treatments	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**
	kg ha^{-1}							
	----------0-30 cm - ----------							
2	18.50	4.40	16.80	2.85	3.60	1.03	4.20	0.23
4	19.80	3.59	23.70	9.18	7.10	2.52	8.30	3.55
7	27.30	14.75	18.50	1.74	32.20	9.77	38.40	20.82
9	28.70	6.43	17.20	1.82	134.60	101.26	100.20	49.70
14	20.10	5.75	18.20	1.74	30.70	26.09	18.00	7.12
$LSD_{(0.10)}$			7.51				44.02	

APPENDIX D

Dixon Annual Grain and Straw Yields without and with P Application

Table D.1 2005 seed and straw yield, and seed and straw %N at Dixon without and with 6.5 kg P ha^{-1}.

	Seed Yield No P Fertilizer		Seed Yield 6.5 kg P ha^{-1}		Straw Yield No P Fertilizer		Straw Yield 6.5 kg P ha^{-1}	
Treatments	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**Mean**	**St Dev**	**Mean**
	kg ha^{-1}							
1	978	283	1161	100	1150	251	1189	177
2	1095	182	1226	392	1186	247	1654	537
3	1336	118	1693	257	1754	684	1812	455
4	3359	255	3982	161	4654	300	5878	666
5	2250	890	2666	672	2843	1136	3616	1309
6	2550	911	2998	670	3720	426	3632	1108
7	3755	558	3626	561	5260	1016	6129	934
8	2221	300	3398	755	2804	302	4494	1249
9	4062	831	3405	398	6368	1482	6055	431
10	3110	671	3636	234	4925	1365	5759	544
11	1631	448	1983	668	2097	899	2973	1414
12	2444	637	2946	534	3286	918	3756	1442
13	2753	260	3710	505	3912	761	5400	558
14	2705	285	3710	244	4215	816	5590	533
15	2955	191	3574	342	4602	282	5803	516
$LSD_{(0.10)}$			580				963	
	Seed %N No P Fertilizer		**Seed %N 6.5 kg P ha^{-1}**		**Straw %N No P Fertilizer**		**Straw %N 6.5 kg P ha^{-1}**	
	Mean	**St Dev**	**Mean**	**St Dev**	**Mean**	**Mean**	**St Dev**	**Mean**
	%N							
1	1.40	0.11	1.49	0.05	0.25	0.04	0.23	0.04
2	1.46	0.06	1.54	0.10	0.23	0.02	0.23	0.01
3	1.53	0.06	1.61	0.03	0.23	0.01	0.24	0.04
4	1.88	0.24	2.07	0.14	0.37	0.11	0.38	0.03
5	1.55	0.08	1.69	0.09	0.24	0.02	0.25	0.02
6	1.79	0.18	1.73	0.02	0.28	0.03	0.25	0.04
7	2.24	0.04	2.41	0.04	0.56	0.07	0.65	0.12
8	1.67	0.11	1.83	0.25	0.26	0.05	0.27	0.10
9	2.39	0.11	2.55	0.10	0.70	0.07	0.87	0.06
10	1.88	0.07	1.92	0.27	0.33	0.04	0.38	0.14
11	1.58	0.08	1.60	0.05	0.23	0.02	0.22	0.02
12	1.57	0.01	1.69	0.06	0.21	0.02	0.24	0.01
13	1.80	0.13	1.77	0.09	0.32	0.06	0.28	0.06
14	2.16	0.14	2.27	0.11	0.42	0.08	0.49	0.07
15	2.30	0.13	2.43	0.08	0.51	0.06	0.64	0.16
$LSD_{(0.10)}$			0.13				0.08	

APPENDIX E

Dixon Fall Soil NH_4^+-N and NO_3^--N without and with P Application

Table E.1 2005 fall soil NH_4^+-N and NO_3^--N at Dixon without and with 6.5 kg P ha^{-1} at 0-30 and 30-60 cm depth increments.

	NH_4^+-N No P Fertilizer		NH_4^+-N 6.5 kg P ha^{-1}		NO_3^--N No P Fertilizer		NO_3^--N 6.5 kg P ha^{-1}	
Treatments	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**
	kg ha^{-1}							
	0-30 cm							
1	9.41	2.45	6.84	0.85	7.90	2.22	9.49	4.79
2	11.88	5.41	10.50	3.99	8.90	1.97	11.56	3.26
3	14.14	6.94	8.82	3.40	9.40	2.03	12.17	3.87
4	15.45	5.43	9.03	3.77	16.40	6.73	19.51	5.34
5	14.35	4.61	9.14	4.25	11.30	4.65	10.93	3.42
6	9.48	3.21	9.11	2.23	12.50	1.36	11.91	2.22
7	14.47	7.04	8.35	3.58	23.30	11.16	23.57	5.95
8	9.60	4.73	6.85	2.04	11.10	1.44	14.10	3.16
9	16.10	8.91	9.79	1.97	33.80	20.38	37.33	16.01
10	14.52	11.86	8.21	3.87	13.20	2.59	15.67	2.50
11	10.85	4.16	8.08	1.12	9.70	1.71	12.29	3.42
12	25.00	26.13	9.54	3.18	12.90	0.68	13.38	3.50
13	12.47	8.69	6.97	1.79	11.50	2.22	14.09	3.41
14	17.22	7.96	7.92	2.33	14.90	3.17	15.36	3.45
15	17.98	5.98	8.67	3.03	17.00	3.56	18.80	4.34
$LSD_{(0.10)}$		7.86				7.15		
	30-60 cm							
1	24.27	27.25	18.92	12.74	3.25	1.20	2.30	1.42
2	13.31	9.33	13.64	11.36	3.03	0.70	1.91	0.91
3	13.46	12.24	22.00	22.49	2.29	1.04	3.36	1.96
4	15.98	6.49	5.02	3.79	8.50	4.78	9.87	7.09
5	13.10	4.93	33.50	27.74	3.99	1.28	3.42	1.22
6	12.53	9.83	25.80	20.20	6.54	4.35	4.51	2.01
7	32.48	33.03	35.51	34.81	35.90	33.62	76.84	46.35
8	18.54	12.70	10.15	8.02	2.99	1.00	10.41	13.46
9	36.98	35.11	50.15	32.93	209.00	164.48	175.51	169.18
10	17.17	13.45	22.58	19.67	6.04	3.78	13.82	10.10
11	24.01	19.96	37.17	40.77	3.00	0.72	3.14	1.65
12	18.28	10.16	9.61	11.29	3.44	1.32	4.26	1.74
13	23.11	10.44	16.20	15.17	4.23	1.19	7.24	4.21
14	21.89	18.24	11.80	8.33	44.70	32.63	16.16	12.31
15	12.65	5.92	6.41	2.16	120.60	130.72	78.04	56.56
$LSD_{(0.10)}$		22.59				61.37		

APPENDIX F

Dixon Annual Grain and Straw Yields without and with P Application

Table F.1 2006 seed and straw yield, and seed and straw %N at Dixon without and with 6.5 kg P ha^{-1}.

	Seed Yield No P Fertilizer		Seed Yield 6.5 kg P ha^{-1}		Straw Yield No P Fertilizer		Straw Yield 6.5 kg P ha^{-1}	
Treatments	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**Mean**	**St Dev**	**Mean**
	kg ha^{-1}							
1	1049	227	844	184	1131	314	716	194
2	996	192	970	187	1002	223	833	209
3	2243	537	2282	293	2507	1068	2051	308
4	2839	320	2364	234	3353	739	2606	585
5	4215	2380	2768	251	2207	2626	2882	333
6	2877	318	2347	539	3596	533	2435	903
7	3079	285	2504	356	3513	292	2911	768
8	2502	368	2199	378	2661	601	2453	691
9	2963	347	2383	240	3449	884	2424	505
10	2737	132	2114	257	3401	489	2468	364
11	1096	205	1188	286	1187	287	1435	349
12	2358	371	2058	261	2417	855	2219	457
13	2312	640	2124	84	2885	555	2326	204
14	2463	603	2172	212	2722	353	2295	507
15	2667	332	2045	393	3108	610	2350	796
$LSD_{(0.10)}$			650				826	

	Seed %N No P Fertilizer		Seed %N 6.5 kg P ha^{-1}		Straw %N No P Fertilizer		Straw %N 6.5 kg P ha^{-1}	
	Mean	**St Dev**	**Mean**	**St Dev**	**Mean**	**Mean**	**St Dev**	**Mean**
	%N							
1	2.16	0.21	2.28	0.09	0.33	0.05	0.38	0.05
2	2.14	0.12	2.32	0.14	0.37	0.05	0.36	0.07
3	2.32	0.08	2.58	0.13	0.43	0.04	0.40	0.09
4	2.66	0.09	2.84	0.22	0.49	0.11	0.45	0.13
5	2.55	0.05	2.75	0.23	0.40	0.04	0.42	0.08
6	2.61	0.13	2.72	0.26	0.48	0.09	0.46	0.12
7	2.82	0.26	2.75	0.15	0.51	0.05	0.53	0.10
8	2.80	0.03	2.86	0.17	0.52	0.08	0.47	0.02
9	2.86	0.25	2.91	0.18	0.69	0.19	0.61	0.08
10	2.73	0.22	2.86	0.29	0.39	0.04	0.39	0.07
11	2.18	0.15	2.29	0.07	0.34	0.03	0.37	0.05
12	2.51	0.16	2.62	0.19	0.44	0.07	0.38	0.12
13	2.54	0.10	2.73	0.23	0.42	0.09	0.35	0.07
14	2.58	0.15	2.91	0.28	0.43	0.05	0.36	0.04
15	2.63	0.16	2.81	0.17	0.57	0.10	0.54	0.13
$LSD_{(0.10)}$			0.18				0.10	

APPENDIX G

Dixon Fall Soil NH_4^+-N and NO_3^--N without and with P Application

Table G.1 2006 fall soil NH_4^+-N and NO_3^--N at Dixon without and with 6.5 kg ha^{-1} at 0-30 and 30-60 cm depth increments.

	NH_4^+-N No P Fertilizer		NH_4^+-N 6.5 kg P ha^{-1}		NO_3^--N No P Fertilizer		NO_3^--N 6.5 kg P ha^{-1}	
Treatments	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**
	kg ha^{-1}							
	0-30 cm							
1	10.11	4.41	10.90	2.43	9.85	0.94	5.69	2.20
2	10.35	1.71	14.80	4.21	9.00	0.43	7.18	2.27
3	9.45	2.10	13.00	4.44	9.95	1.02	7.67	2.54
4	9.65	2.56	13.20	3.60	11.90	3.50	25.26	23.86
5	12.75	2.01	21.65	15.00	14.60	5.15	15.79	11.76
6	12.35	1.32	14.60	4.65	60.90	39.82	15.85	10.74
7	11.70	1.65	14.05	3.16	32.75	34.42	28.77	24.50
8	12.60	5.34	12.25	3.55	28.00	22.77	16.22	11.28
9	9.30	1.57	18.85	5.80	76.95	103.94	23.64	13.13
10	9.10	2.39	16.30	3.89	10.65	1.06	9.68	2.37
11	12.10	1.72	11.95	3.98	9.70	0.35	6.31	1.30
12	12.55	4.08	14.95	3.50	9.35	0.57	7.18	1.64
13	11.35	2.90	14.80	2.21	25.80	11.04	8.18	1.45
14	11.25	2.15	19.70	4.71	28.00	36.00	11.13	3.70
15	12.00	2.01	17.50	4.60	27.70	10.00	44.51	47.91
$LSD_{(0.10)}$		4.91				30.49		
	30-60 cm							
1	11.40	3.66	27.10	24.87	7.80	0.77	4.74	2.29
2	25.10	19.39	15.30	3.61	7.60	0.86	4.15	2.14
3	15.80	10.42	21.80	17.77	7.80	0.52	5.46	2.13
4	14.00	1.13	12.20	3.22	22.30	13.55	20.81	17.37
5	13.00	3.31	26.70	11.63	15.70	5.88	22.35	8.68
6	9.40	1.37	21.20	5.67	29.60	14.43	42.82	37.25
7	19.90	12.14	14.50	1.10	102.00	76.63	82.50	44.33
8	7.60	2.67	20.00	11.37	56.80	15.74	79.76	30.48
9	26.40	33.08	31.50	21.87	368.00	247.50	226.68	36.64
10	20.40	23.86	18.00	2.12	13.00	2.74	21.88	5.78
11	13.00	5.62	16.50	2.22	8.20	0.69	5.02	1.41
12	15.70	6.17	14.60	2.18	8.50	0.68	6.13	2.39
13	10.20	5.68	14.40	3.95	23.60	15.61	19.99	11.08
14	15.10	10.81	14.50	2.36	43.90	19.61	25.26	9.15
15	14.00	7.95	23.50	7.20	288.00	124.06	115.78	70.76
$LSD_{(0.10)}$		13.73				65.75		

APPENDIX H

Dixon Crop N recovery without and with P application

Table H.1 2004, 2005 and 2006 crop N recovery at Dixon without and with 6.5 kg P ha^{-1}.

	Crop N Recovery No P Fertilizer			Crop N Recovery 6.5 kg P ha^{-1}	
Treatments	**Mean**	**St Dev**		**Mean**	**St Dev**
2004 – Canola	----------%N Recovery----------				
4	73.6	27.9		104.4	33.1
7	60.7	29.6		63.3	39.2
9	27.2	12.0		23.1	15.0
10	60.5	36.8		43.1	27.6
13	60.4	59.6		65.9	61.1
14	20.7	24.4		41.0	23.9
15	4.7	2.0		14.3	15.5
$LSD_{(0.10)}$			32.7		
2005 – Wheat	**Mean**	**St Dev**		**Mean**	**St Dev**
4	66.8	7.2		83.3	15.3
7	51.6	10.2		51.7	17.4
9	33.4	8.3		26.8	5.8
10	61.0	20.9		70.1	19.4
13	77.1	9.9		111.4	49.7
14	51.4	12.2		64.7	15.6
15	32.5	2.5		30.3	6.8
$LSD_{(0.10)}$			19.1		
2006 - Flax	**Mean**	**St Dev**		**Mean**	**St Dev**
4	78.9	5.3		62.0	9.9
7	47.0	7.7		34.7	9.4
9	24.7	5.9		17.3	3.8
10	73.9	9.7		51.9	7.2
13					
14	45.1	18.0		40.6	2.0
15	27.9	6.1		20.0	7.2
$LSD_{(0.10)}$			8.5		

APPENDIX I

Melfort Annual Grain and Straw Yields without and with S Application

Table I.1 2004 seed and straw yield, and seed and straw %N at Melfort without and with 40 kg S ha^{-1}.

	Seed Yield No S		Seed Yield Elemental S		Seed Yield Potassium Sulfate		Straw Yield No S		Straw Yield Elemental S		Straw Yield Potassium Sulfate	
Treatments	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**
	kg ha^{-1}											
1	2375	703	2430	1459	2904	604	2318	572	1698	672	2139	569
2	5039	464	5055	511	4656	621	5379	891	3949	154	3977	660
3	4641	704	5211	397	4736	474	5682	579	4547	167	4909	408
4	4997	279	4566	456	4139	670	5124	676	3274	260	3204	249
5	4720	539	5048	255	4497	943	4471	726	4230	522	4558	891
$LSD_{(0.10)}$			769						649			
	Seed %N No S		**Seed %N Elemental S**		**Seed %N Potassium Sulfate**		**Straw %N No S**		**Straw %N Elemental S**		**Straw %N Potassium Sulfate**	
	Mean	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**
	%N											
1	1.43	0.08	1.46	0.15	1.37	0.04	0.26	0.01	0.38	0.05	0.31	0.03
2	2.13	0.08	1.82	0.11	1.94	0.11	0.54	0.09	0.61	0.22	0.56	0.17
3	2.13	0.14	1.97	0.05	2.07	0.07	0.79	0.17	0.66	0.07	0.79	0.07
4	1.89	0.11	1.72	0.05	1.66	0.10	0.48	0.09	0.43	0.08	0.44	0.07
5	1.77	0.09	1.90	0.16	1.93	0.06	0.85	0.19	0.48	0.05	0.58	0.10
$LSD_{(0.10)}$			0.11						0.13			

APPENDIX J

Melfort Fall Soil NH_4^+-N and NO_3^--N without and with S Application

Table J.1 2004 fall soil NH_4^+-N and NO_3^--N at Melfort without and with 40 kg S ha^{-1} at 0-30 and 30-60 cm depth increments.

	NH_4^+-N No S		NH_4^+-N Potassium Sulfate		NO_3^--N No S		NO_3^--N Potassium Sulfate	
Treatments	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**
	kg ha^{-1}							
	0-30 cm							
1	38.40	15.54	62.10	29.86	5.10	1.94	5.20	0.86
2	44.30	4.51	68.10	32.68	9.20	2.83	11.90	8.64
4	35.70	11.67	59.70	30.21	8.80	3.22	6.50	1.89
5	31.90	8.26	62.50	18.53	11.70	2.85	8.20	2.18
$LSD_{(0.10)}$		17.30				3.70		
	30-60 cm							
1	40.80	10.06	61.60	23.40	3.40	1.06	3.80	0.40
2	45.70	13.73	62.10	22.55	3.30	0.76	15.00	21.76
4	40.80	10.61	59.40	26.28	3.70	1.05	3.80	1.06
5	34.10	14.61	54.40	30.39	11.50	5.78	3.20	0.46
$LSD_{(0.10)}$		15.10				10.08		
	60-90 cm							
1	38.00	4.17	61.80	29.49	5.20	1.42	15.80	20.41
2	42.00	11.15	58.40	22.05	5.70	2.29	7.90	4.17
4	36.40	3.12	56.10	21.37	5.10	0.95	5.50	0.82
5	36.50	2.74	54.80	28.59	19.10	9.37	5.50	1.65
$LSD_{(0.10)}$		18.54				9.67		

APPENDIX K

Melfort Annual Grain and Straw Yields without and with S Application

Table K.1 2005 seed and straw yield, and seed and straw %N at Melfort without and with 40 kg S ha^{-1}.

	Seed Yield No S		Seed Yield Elemental S		Seed Yield Potassium Sulfate		Straw Yield No S		Straw Yield Elemental S		Straw Yield Potassium Sulfate	
Treatments	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**
	---kg ha^{-1}---											
1	430	386	309	222	387	189	977	756	786	432	999	271
2	1544	252	1436	454	1576	661	3413	509	3086	1007	3084	1105
3	1153	517	1120	344	1171	228	2414	1025	2198	774	1969	413
4	826	325	635	46	593	250	1717	585	1535	219	1267	489
5	1	0	1322	99	1301	192	2682	1036	3298	221	2646	488
$LSD_{(0.10)}$			387						819			
	Seed %N No S		**Seed %N Elemental S**		**Seed %N Potassium Sulfate**		**Straw %N No S**		**Straw %N Elemental S**		**Straw %N Potassium Sulfate**	
	Mean	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**
	---**%N**---											
1	3.34	0.05	3.22	0.15	3.15	0.12	0.38	0.06	0.40	0.12	0.42	0.10
2	3.53	0.42	3.25	0.33	3.41	0.61	0.33	0.06	0.27	0.03	0.38	0.19
3	3.80	0.19	3.67	0.59	3.65	0.20	0.40	0.06	0.41	0.13	0.39	0.08
4	3.33	0.15	3.17	0.14	3.25	0.07	0.33	0.00	0.34	0.07	0.35	0.06
5	0.00	0.00	3.41	0.17	3.36	0.10	1.29	0.39	0.31	0.02	0.28	0.02
$LSD_{(0.10)}$			0.33						0.16			

APPENDIX L

Melfort Fall Soil NH_4^+-N and NO_3^--N without and with S Application

Table L.1 2005 fall soil NH_4^+-N and NO_3^--N at Melfort without and with 40 kg S ha^{-1} at 0-30 and 30-60 cm depth increments.

Treatments	NH_4^+-N No S		NH_4^+-N Elemental S		NH_4^+-N Potassium Sulfate		NO_3^-N No S		NO_3^-N Elemental S		NO_3^--N Potassium Sulfate	
	Mean	St Dev	Mean	St Dev	Mean	St Dev	Mean	St Dev	Mean	St Dev	Mean	St Dev
	kg ha^{-1}											
	0-30 cm											
1	21.86	3.05	18.10	5.75	18.97	1.32	6.01	2.46	7.78	3.03	6.45	2.71
2	26.29	11.40	18.55	5.19	16.37	5.02	9.28	2.67	7.40	2.49	11.05	8.57
3	22.61	4.40	16.36	4.14	14.85	2.12	12.32	6.00	8.33	4.63	9.77	2.56
4	24.14	4.18	16.47	5.99	20.36	6.55	10.97	3.52	7.89	1.14	9.18	4.22
5	27.93	5.58	20.90	5.50	18.91	2.87	8.80	2.75	10.71	3.03	8.94	1.44
$LSD_{(0.10)}$			5.51						3.77			
	30-60 cm											
1	22.29	3.52	21.45	3.50	22.85	1.19	0.05	0.09	0.61	0.78	0.15	0.20
2	23.42	3.28	21.48	4.00	20.26	4.22	0.77	0.52	1.41	0.98	2.69	4.03
3	25.04	8.01	19.32	4.82	21.04	5.46	1.26	1.37	1.89	2.42	1.31	1.87
4	24.73	2.86	16.90	8.61	20.89	1.87	0.22	0.37	0.17	0.29	0.95	0.96
5	27.94	8.50	22.74	7.73	20.08	6.31	1.97	1.87	1.06	1.27	2.19	0.99
$LSD_{(0.10)}$			6.37						1.68			

APPENDIX M

Melfort Annual Grain and Straw Yields without and with S Application

Table m.1 2006 seed and straw yield, and seed and straw %N at Melfort without and with 40 kg S ha^{-1}.

	Seed Yield No S		Seed Yield Elemental S		Seed Yield Potassium Sulfate		Straw Yield No S		Straw Yield Elemental S		Straw Yield Potassium Sulfate	
Treatments	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**
	---kg ha^{-1}---											
1	1472	350	1527	205	1716	784	1323	278	1601	289	2771	1956
2	4959	826	4424	824	4033	1081	3989	334	3636	783	3640	702
3	4628	498	4951	156	4839	429	4232	908	4304	647	3786	518
4	5253	203	5647	315	5094	383	4684	714	4758	670	4496	510
5	2261	1141	4883	732	4244	582	2556	921	4067	170	3806	697
$LSD_{(0.10)}$			765						935			
	Seed %N No S		**Seed %N Elemental S**		**Seed %N Potassium Sulfate**		**Straw %N No S**		**Straw %N Elemental S**		**Straw %N Potassium Sulfate**	
	Mean	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**
	---**%N**---											
1	1.47	0.13	1.43	0.04	1.52	0.05	0.56	0.05	0.60	0.10	0.54	0.09
2	1.44	0.08	1.42	0.05	1.54	0.07	0.57	0.19	0.47	0.03	0.57	0.08
3	1.73	0.06	1.58	0.10	1.66	0.03	0.68	0.07	0.61	0.13	0.66	0.15
4	1.78	0.09	1.78	0.07	1.71	0.14	0.89	0.25	0.76	0.25	0.69	0.15
5	1.97	0.17	1.47	0.05	1.49	0.06	1.75	1.03	0.58	0.19	0.47	0.06
$LSD_{(0.10)}$			0.11						0.36			

APPENDIX N

Melfort Fall Soil NH_4^+ and NO_3^- without and with S Application

Table N.1 2006 fall soil NH_4^+-N and NO_3^--N at Melfort without and with 40 kg S ha^{-1} at 0-30 and 30-60 cm depth increments.

Treatments	NH_4^+-N No S		NH_4^+-N Elemental S		NH_4^+-N Potassium Sulfate		NO_3^-N No S		NO_3^-N Elemental S		NO_3^--N Potassium Sulfate	
	Mean	St Dev	Mean	St Dev	Mean	St Dev	Mean	St Dev	Mean	St Dev	Mean	St Dev
	kg ha^{-1}											
	0-30 cm											
1	13.50	6.10	13.20	4.56	23.05	6.74	8.17	1.59	8.80	4.68	8.90	2.68
2	20.15	8.32	12.90	1.19	17.40	7.45	11.05	1.76	9.90	1.54	12.20	1.56
3	17.55	4.09	17.30	6.98	15.45	5.06	8.14	1.54	15.40	7.66	9.45	1.54
4	15.40	0.99	15.70	4.10	18.05	6.26	13.35	2.76	12.90	8.04	11.50	5.41
5	16.80	2.66	17.80	1.06	19.10	6.66	18.35	17.45	11.70	6.39	12.70	1.15
$LSD_{(0.10)}$			6.24						7.32			
	30-60 cm											
1	12.20	5.89	11.20	3.68	17.80	3.64	3.40	0.22	3.34	0.39	4.38	0.69
2	14.30	9.22	20.10	11.44	21.20	4.09	3.69	0.85	3.67	0.09	5.10	0.76
3	13.70	4.54	14.00	3.50	20.00	4.99	4.03	0.69	5.01	1.53	5.06	1.06
4	13.30	1.54	15.20	1.82	22.10	5.06	7.90	2.45	8.94	9.91	7.30	3.26
5	17.00	10.76	17.00	2.45	19.20	6.84	4.99	2.33	3.70	1.30	4.90	0.68
$LSD_{(0.10)}$			7.32						3.57			

APPENDIX O

Melfort Crop N recovery without and with S application

Table O.1 2004, 2005, and 2006 crop N recovery at Melfort without and with 40 kg S ha^{-1}.

	Crop N Recovery No S		Crop N Recovery Elemental S		Crop N Recovery Potassium Sulfate	
Treatments	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**
2004 - Oat	----------%N----------					
2	144.4	22.6	112.6	12.2	99.2	29.5
3	77.8	6.0	69.5	8.0	68.2	7.4
4	29.6	3.1	19.5	3.4	13.6	5.2
5	101.7	17.2	94.8	12.6	83.3	11.7
$LSD_{(0.10)}$			16.6			
2005 - Canola	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**
2	52.9	17.3	47.2	24.5	58.6	51.8
3	19.9	13.6	20.4	10.5	18.4	3.3
4	4.3	3.7	3.4	0.8	2.0	2.5
5	17.4	4.5	53.2	7.6	43.8	9.1
$LSD_{(0.10)}$			22.0			
2006 - Barley	**Mean**	**St Dev**	**Mean**	**St Dev**	**Mean**	**St Dev**
2	77.5	25.2	57.1	16.7	50.6	21.7
3	46.7	7.0	42.9	4.1	38.5	4.8
4	31.0	3.7	31.1	6.7	23.1	4.3
5	65.3	12.6	80.1	17.7	52.3	17.7
$LSD_{(0.10)}$			16.7			